SAFETY ASSURED FINANCIAL

EVALUATION OF MAINTENANCE

A Dissertation

by

VERA ERGUINA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2004

Major Subject: Nuclear Engineering

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Approved as to style and content by:

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ABSTRACT

Safety Assured Financial Evaluation of Maintenance. (May 2004)
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Chair of Advisory Committee: Dr. Paul Nelson, Jr.

Management decisions in complex industrial facilities usually consider both the economic and environmental aspects of the plant's performance. For nuclear power plants (NPPs), safety is also a very substantial issue. The objectives of this dissertation are to develop and demonstrate a novel useful conceptual model that could be used to allocate maintenance funds for a nuclear power plant in such a way as to meet all specified safety requirements and objectives, while achieving a high degree of economic performance.

The model is based on the general theory that the reliability of a plant at any time is a function of its initial reliability and the maintenance history of the individual plant components (Smith, 1997). Such a model can assist in evaluating strategic management decisions regarding allocation of funds for nuclear power plant maintenance. It could be used as a simulation tool; various scenarios could be studied to answer "what if" questions. Simulations of this type will allow a better understanding of the relationship between maintenance, economic performance, and safety, and consequently will lead to better decision making.

The novelty of this model is tied to the intimate relationship that it develops between maintenance activities at a nuclear plant, and their relationship to prescribed safety requirements and to the economic performance of that plant.

ACKNOWLEDGMENTS

First I would like to thank everyone from the Texas A&M University Nuclear Engineering Department who made it possible for me to study at this university.

I would like to thank my adviser Dr. Paul Nelson for his support during the work on this dissertation.

I would like to thank Dr. Joe Braun for making it possible to work on this dissertation at Argonne National Laboratory - East. I would also like to thank Nicholas Lugansky for his contribution into the prototype model.

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INTRODUCTION

During last three-four years the nuclear industry has started to show its interest to studies oriented on combining operational and economic sites of nuclear power plant operation. One of the leading roles here is played by South Texas Project (STP) nuclear power plants. During these last years they have been working on the so-called risk-informed asset management (RIAM) approach (Liming and Kee, 2002; Grantom, 2003). This approach "involves the modeling and probabilistic quantification of decision support performance indicators to aid plant decision-makers in determining not only which plant improvement investment options should be implemented, but also how to prioritize plant resources for their implementation based on their predicted levels of profitability" (Liming and Kee, 2002). The benefits of applying such approach were demonstrated by STP on one of their system – the feed water system in 2003 (Kee et al., 2003). Since then they are continuing to implement the RIAM concept on their other systems, expecting by some time in the future to cover all systems one by one.

The goal for this dissertation was to develop a model of a PWR-design nuclear power plant, and to demonstrate how maintenance allocations can influence all three (operational, economical, and safety) groups of key plant performance indicators. The present version of the model includes only super-components of a PWR system, but has a built-in capability to be extended by including other components (from both super- and sub-levels) if needed. The model is a substantial extension of an earlier prototypical model developed as a joint work with J.C.Braun and N.Lugansky, of the Argonne National Laboratory, and presented at the 2002 Winter Meeting of the American Nuclear Society (Braun et al., 2002).

The dissertation is divided into two parts. The first part describes the prototype model "Nuclear Power Plant Maintenance Economics Model" (Braun et al., 2002). The second part is dedicated to the new model that was called the Safety Assured Financial

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This dissertation follows the style and format of Nuclear Engineering and Design.

Evaluation of Maintenance (SAFE-M) model and is a substantial extension to the prototype model. But, while the prototype model has only operational (in terms of capacity factor) and economic (in terms of revenues, costs, profits) performance indicators, the SAFE-M model works also with the safety side of nuclear system operation (core damage frequency is used as an indicator here).

PROTOTYPE MODEL

Hypotheses

The primary objective of the prototype model was to understand the correlation between maintenance spending and reliability of a system. Indeed, even though such a correlation is commonly observed and practically considered common sense, the impact of maintenance allocation on system reliability, particularly numerically expressed, is still largely unknown. Therefore, to study the behavior of the system under various financial stimuli we assumed that there must be some response to the expenditure of funds, usually some change in system reliability and performance. To justify our hypothesis the following considerations were taken into account.

According to the definition of reliability, an item of equipment or a system is reliable if it operates without failures for a prolonged period of time; otherwise it is unreliable (Mercier, 1993). The study by J.P. Mercier determined the relationship between preventive maintenance (PM) effort and system reliability (Figure 1). PM is a type of maintenance that is performed periodically, in order to reduce the likelihood of system breakdown. The curve has an asymptotic nature; thus it has a point of diminishing return when PM allocations will not have a positive net value.

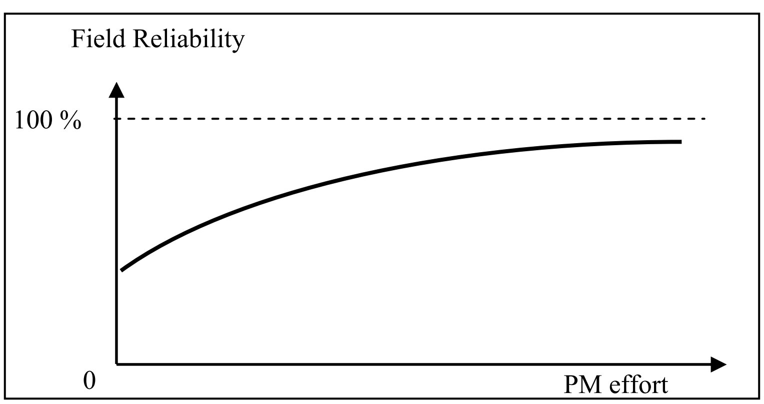


Figure 1. Reliability vs. preventive maintenance effort

Based on the aforementioned reliability definition, more reliable equipment is equipment that fails less often. This characterization of equipment reliability is called the failure rate (FR). FR can be calculated as the inverse of the sum of mean time between failures (MTBF) and mean time to repair (MTTR).

$$FR = \frac{1}{MTBF + MTTR} \tag{1}$$

where MTBF - average time before failure of a component occurs;

MTTR - mean time to repair or replace a failed system component.

For this study the MTTR is assumed to be constant in time, for a given piece of equipment. It is evident from Eqn. 1 that the higher the value of MTBF, the lower the value of FR.

Consequently, the following chain of dependencies can be created:

$$MTBF \propto \frac{1}{\mathrm{FR}} \propto \text{Reliability} \propto \text{PM effort} \propto \text{Funds for Maintenance}$$

This chain of dependencies allows us to replace Figure 1 with Figure 2. Figure 2 shows MTBF as a function of funds allocated to maintenance.

To describe mathematically the correlation between MTBF vs. dollars spent shown in Figure 2, the exponential law is applied,

$$MTBF(\$) = C \cdot (1 - e^{-(a \cdot \$ - b)}) \tag{2}$$

where

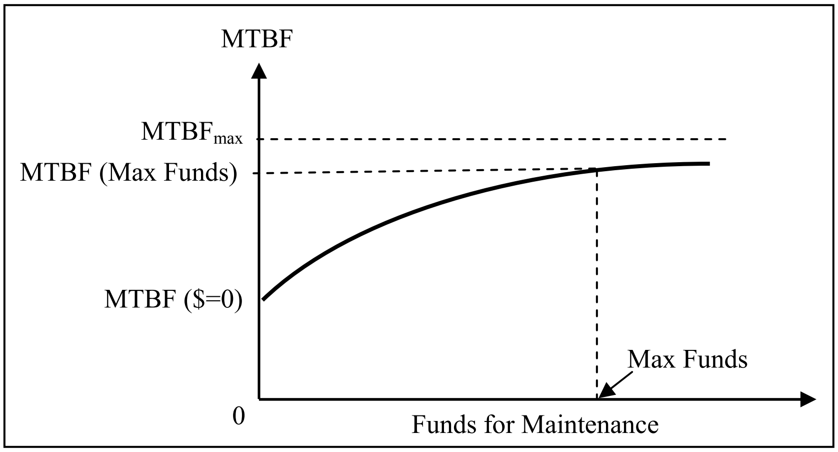


Figure 2. MTBF vs. dollars spent for maintenance

$$b = \ln\left[1 - \frac{MTBF(\$ = 0)}{C}\right] \tag{3}$$

and

$$a = \frac{1}{Max\,Funds} \cdot \ln\left[\frac{1}{e^b}\left(1 - \frac{MTBF(Max\,Funds)}{C}\right)\right] \tag{4}$$

In these equations C is the number of days per operating period (MTBF$_{max}$ on the graph), and *a* and *b* are coefficients calculated from the problem boundary conditions (the given values at funds for maintenance equal zero and "Max Funds"). The "Max Funds" parameter represents an arbitrary maximum annual funds allocation for maintenance.

As the prototype model is intended to provide proof of principle, all equipment at the plant is divided into three large categories, based on their functional principles. They are:

- Mechanical, Instrumentation & Control (MI&C);
- Electrical (ELEC); and
- Structure (STR).

Additionally, the model takes into consideration Human Error (HE), which represents personnel actions that lead to a loss of plant capacity. In this case, improved human performance is presumed to result from funds spent on training, requalification, and education. For each of these four groups a curve similar to the one shown on Fig. 2 is built. It is assumed that the major contributions to system failures are due to human errors, then MI&C, Electrical and Structure components.

Aging

The model addresses aging by assuming that equipment FR changes with time as in Figure 3. At the early stage of operation, also known as the burn-in period, FR decreases rapidly as manufacturing and construction defects are repaired. As the system stabilizes the FR levels off. This second stage is called the useful life period and during this stage FR increases slowly. As equipment wears out, the degradation becomes dominant, and the FR increases. This third stage is called the wear-out period. If all three stages of FR vs. time are plotted, the curve resembles a bath-tub. This bath-tub curve of Figure 3 summarizes the life-time aging of equipment or component (Kuo et al., 2001).

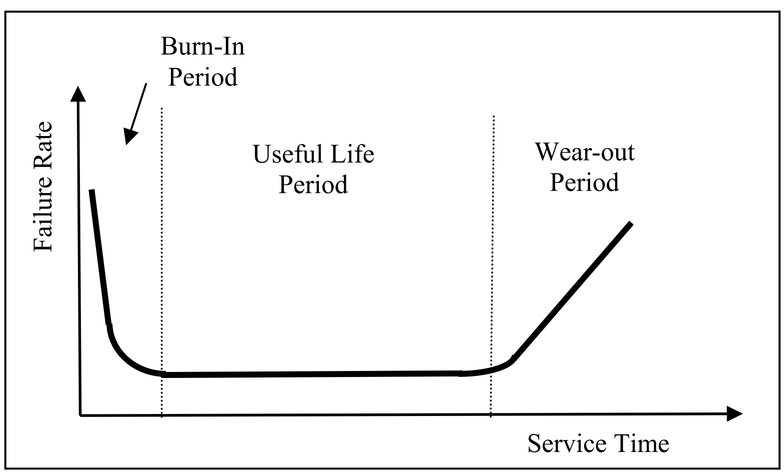


Figure 3. Bath-tub curve

The wear-out period for nuclear plants is not universally accepted since overhauls and replacements may eliminate it. Also, wear out does not occur at the same point in plant life for all components. Example, steam generators wear out occurs in 20 years for many plants. However, the prototype model assumes some average equipment wear-out rates.

Many manufacturers provide a burn-in period for their product prior to delivery, which helps to eliminate a high portion of the initial failures (Anderson and Neri, 1990). Since the model assumes that the actual operating time for equipment starts after the burn-in period, it is not taken into consideration. See Figure 4 below for the modified “bath-tub” curve used in the prototype model.

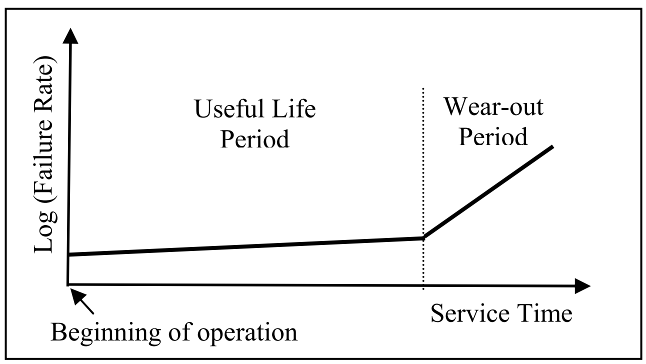
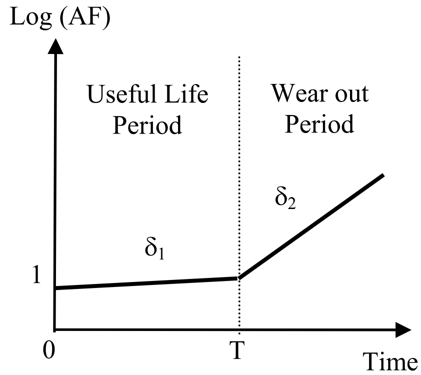


Figure 4. Modified bath-tub curve

To model this “bath-tub” behavior in the prototype model it is also assumed that the present failure rate (FR) differs from the future failure rate (FR_{age}) by the coefficient called aging function (AF).

$$FR \cdot AF = FR_{age} \tag{5}$$

This coefficient changes with the bath-tub law and it forces failure rate to change with the same law. AF = 1 corresponds to a new system where no aging has taken place (Figure 5).



$$AF = \begin{cases} (1+\delta_1)^t, 0 < t < T \\ (1+\delta_1)^T (1+\delta_2)^{t-T}, t > T \end{cases}$$

where

δ_1, δ_2 – aging rates (% of degradation /year),
T – time where degradation factors become dominant

Figure 5. Aging function

Consequently, as the system wears with time, each component's mean time between failures changes too. Thus, after each operating year the value of component MTBF has to be recalculated. From Eqns. 1 and 5, one computes

$$MTBF_{age} = \frac{MTBF}{AF} + MTTR\left(\frac{1}{AF} - 1\right). \tag{6}$$

Optimization

The model contains two interconnected modules, financial and maintenance. The financial module represents plant management. The management determines an annual plant budget, including the portion for maintenance. These funds go to the maintenance module, which represents the plant maintenance department. The goal of this module is to spread the allocated funds among system components. The module has the following two different options here.

1) *Direct plant management decision*. In this option funds in the amount defined by the management decision go directly to particular system components.

2) *Optimization subroutine*. The model automatically allocates funds to that system component which will yield the lowest plant time out of service (PTOOS).

The advantage of choosing the optimization for funds distribution is shown in the "Results" section below (see Case 1).

Reliability has already been mentioned as one of the measures that indicate the performance of a system. The other measure, which "is equally, or even more important, is the percentage of time that the equipment is able to produce its rated production or service" (Mercier, 1993). This measure is called availability. Based on this definition, the more available the system is the lower its time out of service (time the system is unavailable to perform its designed functions due to failure of one of the system components). This led to selection of the system time out of service as an optimization parameter.

Analyses of the system's initial data lead to creating the Pareto Diagram (Six Sigma Community in Europe website) shown on Figure 6. This diagram indicates the relative importance of the components for system time out of service in the order from the largest to the smallest. It is obvious from the figure that the major contribution to PTOOS comes from human errors. Thus, to make a system more reliable, the performance of the HE component should be improved first. After HE reaches "Level 1" on the diagram the improvement effort should go to both HE and MI&C components till they reach "Level 2" mark, and so on.

The model uses the Pareto Diagram's principle to determine the priority for funds allocation. Figure 7 shows model's analogy of this diagram. Four curves correspond to four groups of components. Arrows show the funds allocation process.

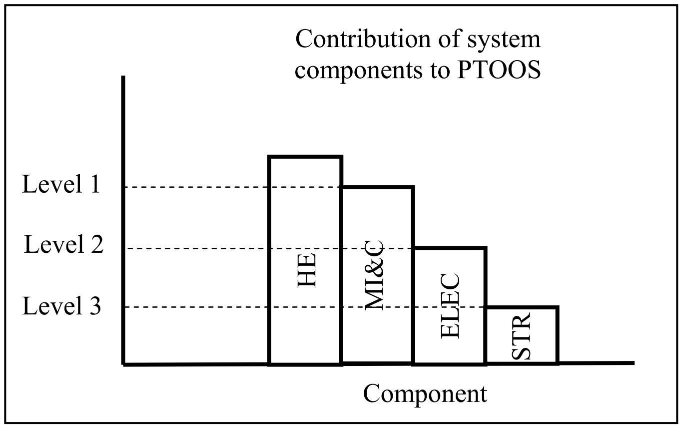


Figure 6. Pareto diagram for the system components

The aforementioned optimization parameter, PTOOS can be derived from MTTR and MTBF.

$$PTOOS = \sum_i TOOS_i = \sum_i FR_i \cdot 365 \cdot MTTR_i \\ = \sum_i \frac{365 \cdot MTTR_i}{MTBF_{age,i} + MTTR_i} \tag{7}$$

The factor of 365 is used here to transform PTOOS from units "years" to "days".

As aforementioned, MTTR is a mean time to repair or replace a failed system component. The model applies this definition to mechanical, instrumentation and control, electrical, and structural components. MTTR, in case of a human error, is an average time needed to eliminate the consequences of a human error that led to plant shutdown (or CF loss).

HE is a unique component of the model. To prevent a human error the plant needs to allocate funds for personal training and/or requalification. Additionally, HE has an impact on other plant systems since personal mistake can lead to a number of different system failures.

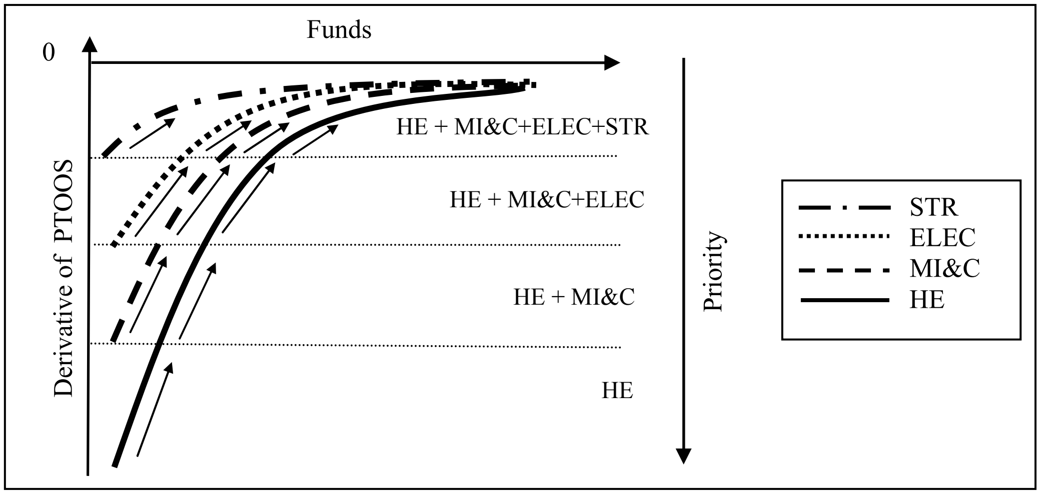


Figure 7. Priority for funds allocation

The following four steps are used to find optimal allocation of the funds:

1. Division of the maintenance budget received from the financial module into small increments.
2. Examination of the four maintenance areas to determine which one will yield greatest positive change of system Time Out of Service and consequently of system availability (Pareto Diagram).
3. Allocation of the small increment of funds to the chosen area.
4. Repetition of steps 2 and 3 until all annual funds are allocated.

Refueling

Every NPP has a refueling outage every 12-24 months. These outages are by far the longest outages modern plants have, since most maintenance is conducted on-line nowadays. Therefore, it is fair to assume that the total plant out of service time per given year is equal to the time the system is down due to component failure and time to refuel, as expressed by

$$PTOOS_{tot} = PTOOS + T_{refuel} \tag{8}$$

Since the model is often used to model plant operation for long periods, where refueling creates unnecessary oscillation of examined data, a “smear refueling” option was built into the model. This feature spreads the refueling time throughout the period between refueling (Figure 8).

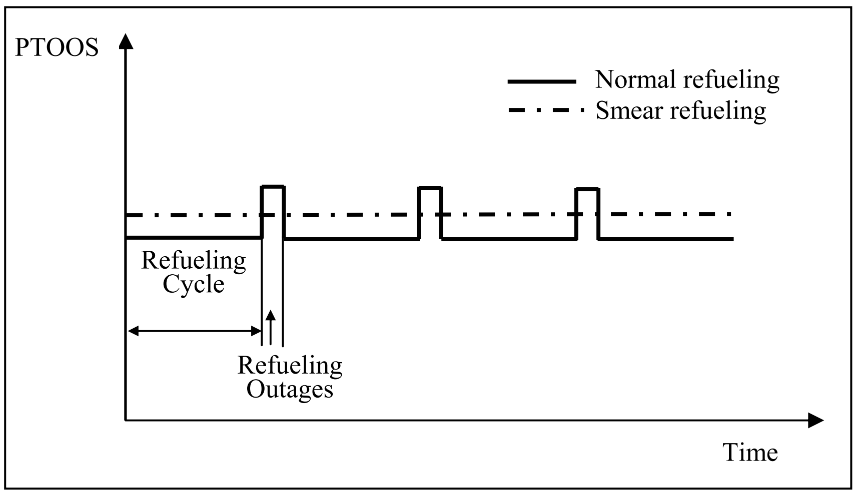


Figure 8. "Smear" and normal refueling

The formula used for “smear refueling” feature is

$$T_{smear\_refuel} = \frac{T_{refuel}}{Cycle\ length} \cdot 365 \tag{9}$$

Units of T_{smear_refuel} is years.

At the end of the year these days are added to TOOS

$$PTOOS_{tot} = PTOOS + T_{smear\_refuel} \tag{10}$$

Capacity Factor

Based on Eqn. 10 the model calculates an average plant capacity factor (system availability) for the period, normally a year.

$$CF = 1 - \frac{PTOOS_{tot}}{365} \tag{11}$$

Obviously, CF will differ based on the methods of funds allocation chosen, optimization or direct allocation.

Plant Economics

Plant capacity factor is provided to the financial module where it is used to evaluate the financial performance of the plant and prepare financial statements.

First, the average price of electricity (APE) is determined since the plant has industrial, commercial, residential, and municipal customers:

$$APE = \sum_{i} Share_i \cdot Price_i \tag{12}$$

where i refers to different type of electricity customers.

Then, the Net Sales are calculated:

$$Net\ Sales = APE \cdot N \cdot T \cdot CF \tag{13}$$

where N - Plant capacity,

T - Hours per operating period,

CF - Average capacity factor.

The Net Sales value and other financial data are used to generate various financial statements. The model has a great amount of initial financial data on NPP operational expenses, fuel cost, and other costs, which allows the model to calculate plant's profit per model cycle (week, month, quarter, year) as well as to generate Net Income Statement and other relevant financial statements.

Based on the financial results for the period the financial module determines the new maintenance budget and sends it to the maintenance module. This cycle is repeated every period.

Benefit/Penalty Function

Each facility implements activities that reduce the effects of usage and aging. These effects include maintenance activities such as lubrication, corrosion protection (painting), etc. To take into account such activities the model has a Benefit/Penalty Function (B/PF). Figure 9 shows how this function affects the natural aging. In this work we assume that natural aging is aging that occurs when minimal recommended maintenance is performed (this amount is assumed to be 25M$ per year in the model). A penalty on aging is applied if allocated funds are not sufficient to prevent the natural aging effect, and benefits are applied if the funds exceed the necessary amount that counteracts the natural aging effect.

Additionally, after running the model an observation was made that the CF did not increase nor decrease realistically when maintenance funds were allocated. The B/PF, thus was a corrective function to improve model performance.

From Figure 9:

$$(AF - 1)_{penalty\,/\,benefit} = (AF_{natural} - 1) \cdot W_{age} \tag{14}$$

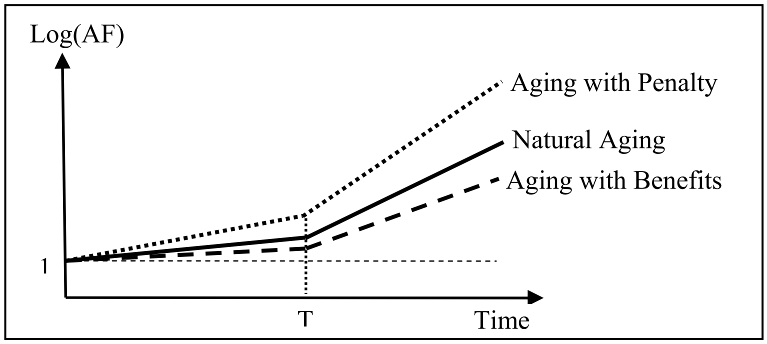


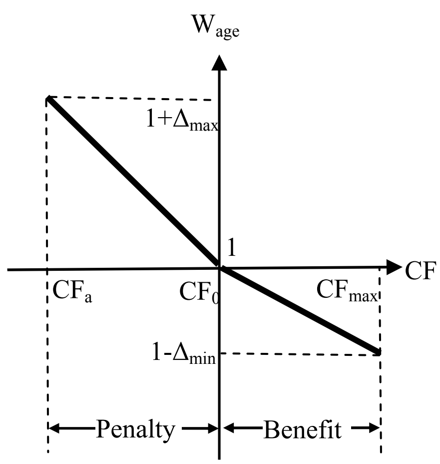
Figure 9. Aging function with benefit/penalty function

where W_{age} – aging weight (Figure 10) is

$$W_{age}\Big|_{total\ \ for\ year\ k} = \prod_{i=1}^{k-1} W_{age,i} \tag{15}$$

Thus, the component aging in any year depends on the component maintenance history.

The Benefit/Penalty function allows us to model preventive maintenance activities that, indeed, require a steady outlay of funds, but do not reap benefits until later.



$$W_{age,i} = \begin{cases} 1 + \dfrac{CF_0 - CF_i}{CF_0 - CF_a} \cdot \Delta_{\max}, & \textit{Penalty} \\ 1 + \dfrac{CF_0 - CF_i}{CF_{\max} - CF_0} \cdot \Delta_{\min}, & \textit{Benefit} \end{cases}$$

where

CF_a – CF with “natural aging” only

CF_{max} – maximum possible CF for the system (from initial data with no outages)

CF_0 – CF at t = 0 (beginning of operation)

Δ_{max}, Δ_{min} – max penalty or benefits

Figure 10. Aging weight

Software

The prototype model is developed using system dynamics methodology and is implemented using iThink^{TM} Software.

This software was chosen for the following reasons:

- has dynamic capability that allows not only to model the system but, also to study its behavior;
- easy to use; it is unnecessary to be a good programmer to create a model in iThink;
- user-friendly interface;
- works with Microsoft Excel, which allows using Excel graphical capabilities to plot charts.

The other goal of using iThink was to show that system dynamics tools could be used to conduct such studies.

Results

The model was tested on many cases. Below are several cases that demonstrate some of the model capabilities. The numerical expression of any parameters in the model depends on the initial data, which depends on the particular system. Since the model was not created for any particular system and uses some average US nuclear power plant data, obtaining logically expected behavior of the system was the main goal.

Case 1. Work of Optimization

The goal for this case was to test whether the optimization process provides any real benefits. When the optimization function is turned off, funds for maintenance, in this case 40M$ per year, are distributed among components on an equal basis; each gets the same amount of funds (see dashed line in Figure 11). When the function is turned on, funds for maintenance are distributed by optimization process described above. The dashpot line in Figure 11 shows the capacity factor when funds are distributed using the optimization procedure. It can be seen from this figure that the difference between the two allocation schemes chosen accumulates at about one percent per year in the capacity factor. Here ANP is the abbreviation for accumulated net profit. Thus, for this particular maintenance policy benefit in ANP from optimization is about 300 millions of dollars. The change at year 20 in slope of the curve is due to a different equipment aging rate before and after year 20 (see discussion of bath-tub curve above).

However, after examining additional cases the results showed that the benefit of one percent is not constant. In fact, it is a function of two parameters: maintenance funds and time (Figure 12).

Figure 13 shows the same results in terms of accumulated net profit.

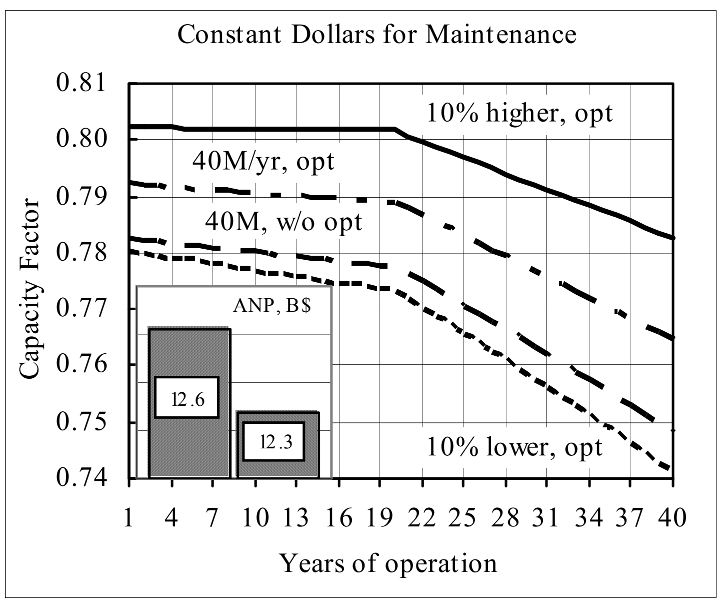


Figure 11. Optimization benefits

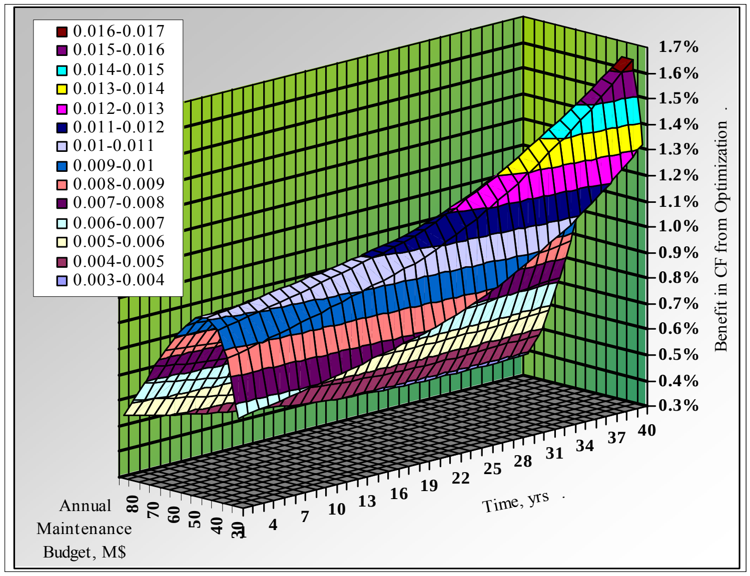


Figure 12. Benefit in CF from optimization vs. equal distribution

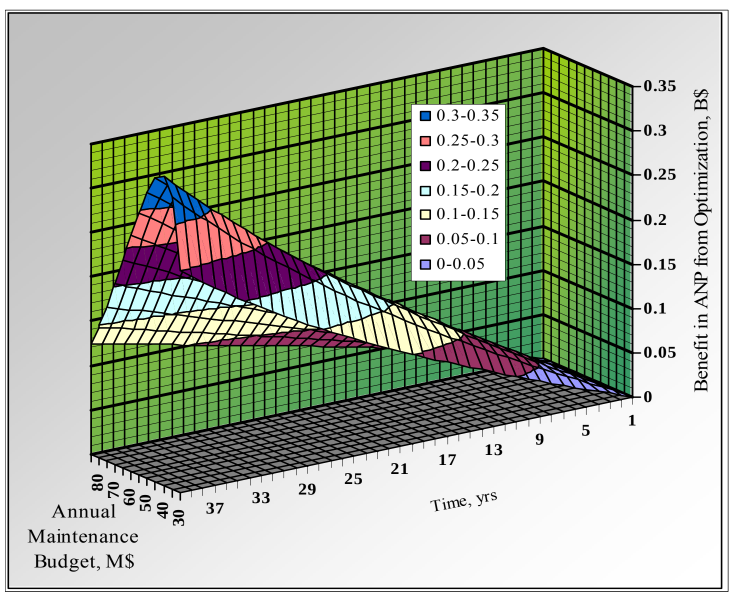
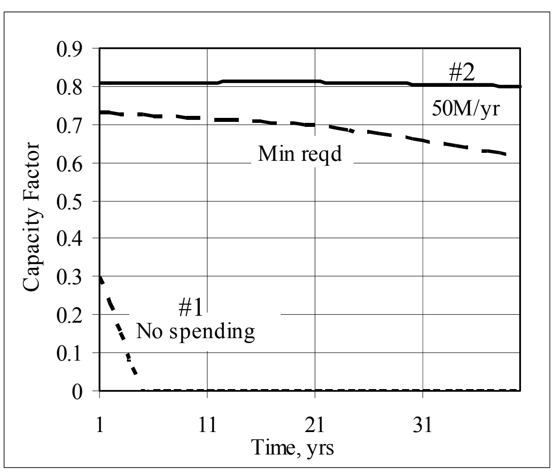


Figure 13. Benefit in ANP from optimization vs. equal distribution

Case 2. Work of Benefit/Penalty Function

This case was studied to examine the work of another built-in function of the model, the Benefit/Penalty function. Figure 14 summaries the results obtained for this case. The curves on the left side of this figure show the nature of B/PF work. Curve #1 demonstrates how plant performance is penalized when annual funds for maintenance, in this case $0 per year, are less then minimum required amount. Curve #2 shows how plant performance enhanced when funds, in this case $50M per year, are above the minimum amount.

The right graph demonstrates plant performance with and without B/PF under two different maintenance spending policies. The two lower curves on the right figure represent an example of a plant policy when spending for maintenance is not sufficient to cover equipment aging effect. As described above, a plant is penalized for such policy and, in this particular example, after some time the accumulated penalty results in complete plant capacity loss (see the lowest line on Figure 14). The upper curves show the case when maintenance budget is more then sufficient to cover system aging. Here, the benefit part of the function works. Again, a good maintenance policy at the plant accumulates some benefits, which leads to an increase in CF with time.



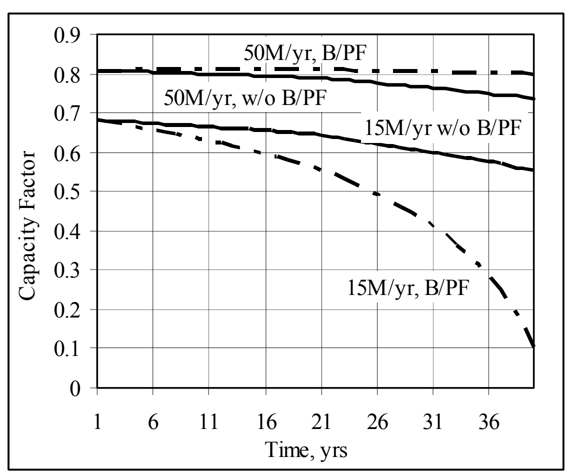


Figure 14. Work of benefit/penalty function

Case 3. Optimal Annual Maintenance Budget

Case 1 (Figure 11) above showed that the more spent on maintenance the higher is the capacity factor. However, large maintenance spending affects the financial performance of the system. Thus, even with higher capacity factor the system's profitability can go down. The goal for this case was to see whether some optimal maintenance spending exists. It compares a series of lifetime calculations of plant capacity and related profitability vs. different constant annual maintenance allocations.

The results are presented on Figure 15. It can be see that from the plant profitability standpoint there is an optimum annual spending for maintenance.

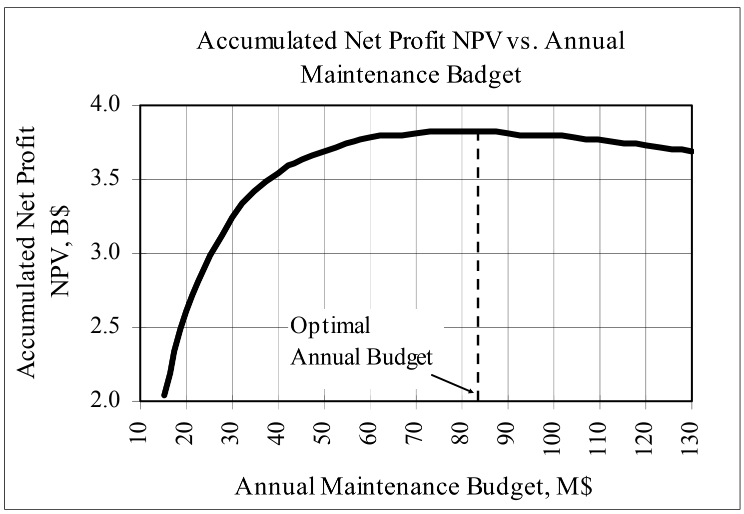


Figure 15. Optimal annual funds for maintenance

Case 4. Constant Capacity Factor

This case assumes that a decision to maintain a constant average capacity factor is made. The model then estimates how much maintenance funding is needed to accomplish the set goal. Figure 16 shows results for this case when the funds allocated for maintenance offset system's aging effect (annual CF was maintained at the level of about 73%).

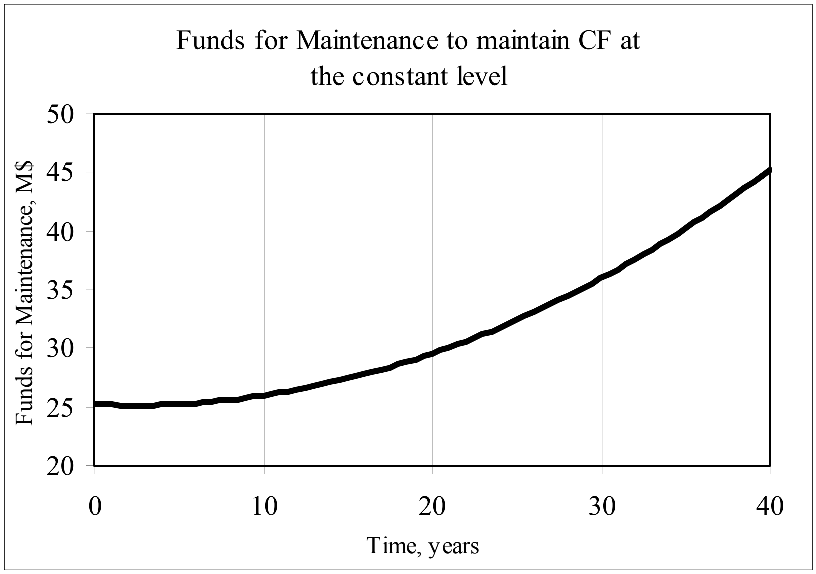


Figure 16. Maintaining constant CF during operating years

The maintenance spending increases with time because of system components aging. The case shows that in order to maintain the system at the same performance level the maintenance budget would have to rise exponentially.

Case 5. Plant Life Extension (PLEX)

This case models replacement of steam generators (SG) prior to life extension. With aging, SG reliability decreases, which affects an entire system. When to replace the aging SGs poses a dilemma, since the sooner SGs are replaced the better system performance will be; however, the later SGs are replaced the newer is the system for the remaining years of licensed operation. Four curves on Figure 17 represent results for this case. Each curve corresponds to different degradation rate of SGs. It is visible from the figure that there is an optimum time for replacement of degrading component (in this case SGs) to maximize plant net profit.

Figure 18 is another way to present this case. It shows the correlation between time to upgrade and the component degradation rate. The results conclude that from the system profitability point of view the more rapidly equipment degrades the sooner it will need to be replaced.

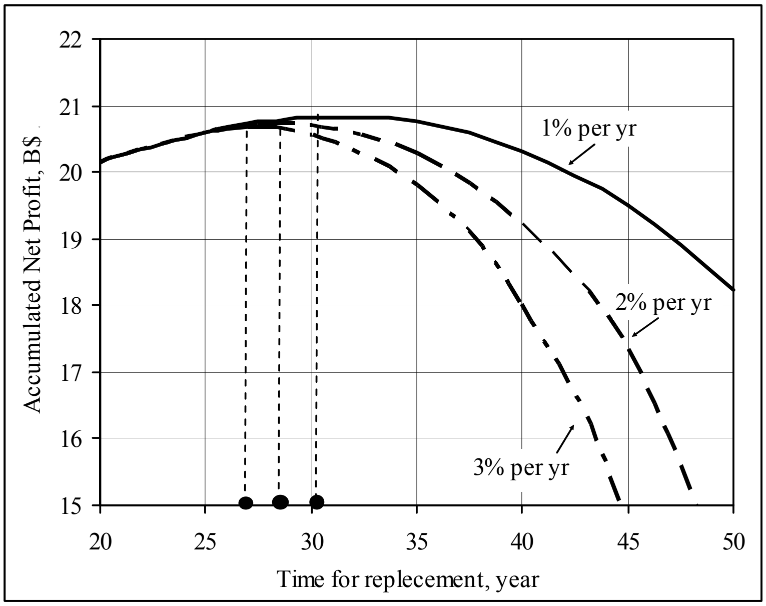


Figure 17. Optimal time for upgrade

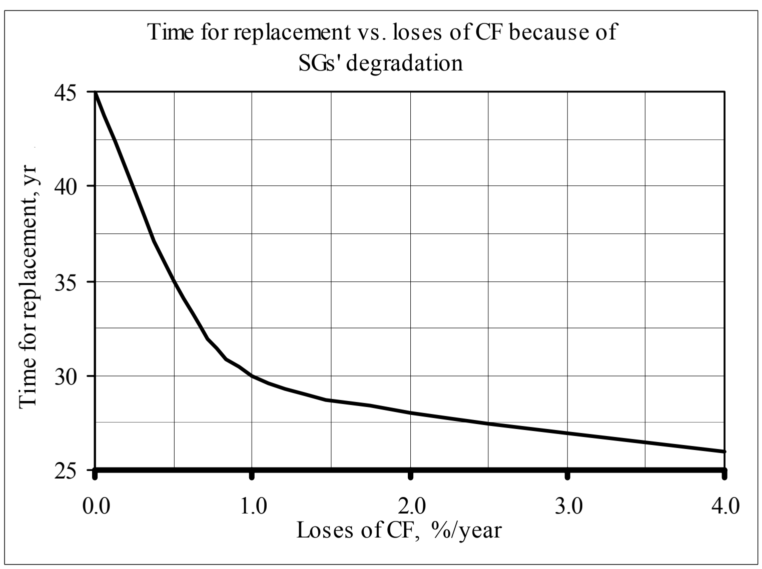


Figure 18. Time to upgrade - degradation of SGs relation

Deltas of the Model

Several features of the prototype model prevent it from providing simulations at the level of detail necessary to support real operational decisions at specific plants. These deficiencies of the prototype model include the following:

A. The four groups of components used in the prototype (mechanical, instrumentation & control, electrical, structural, and human errors) provide too coarse an aggregation to permit either operationally useful maintenance allocation decisions or validation of the model against plant operational data.

B. The prototype model assumes that failure of a component in any one of the four broad component groups will result in plant shutdown, whereas in fact the possible consequences at the plant level of component failure covers the range from "no effect" to "core damage."

C. The prototype model provides no mechanism for including the effect upon plant safety of decisions regarding allocations for maintenance.

D. The software environment within which the prototype was implemented is not sufficiently flexible to support a model that will provide for the complexities necessary to accommodate the extensions to the prototype that are suggested by the three preceding considerations.

Conclusions

The goal of this work was to create a simple tool that will help us to develop insights about nuclear power plant maintenance allocations, and the impact of such allocations on plant economic performance. Also, the model allows us to look at a variety of plant life extension options.

The model is created using iThink system dynamics software. The model explores the connection between the maintenance spending and financial performance of a plant. It allows

- to estimate the optimum maintenance allocation to maximize plant profitability;
- to examine the impact of maintenance expenditures on plant reliability;
- to consider equipment aging; and
- to demonstrate how maintenance policies can influence the cost of life extension.

The model can be used as a simulation tool. By changing initial parameters on the iThink interface various scenarios could be studied to answer the “what if” questions. This simulation allows better understanding of the system, which consequently will lead to better decision making.

Although this is a simple model, it forms a beginning for a larger project that can lead to the development of a model that will enable NPP management to make better policy decisions on maintenance spending.

THE SAFE-M MODEL

System Description

The SAFE-M (Safety Assured Financial Evaluation of Maintenance) model is based upon a typical four-loop pressurized water reactor (PWR). This type of reactor was chosen because it is most widely used in the USA. Figure 19 shows a simplified scheme of a PWR design (two of the four primary coolant loops are shown). The figure does not show the safety components, such as control rods and emergency cooling system, are used in the model.

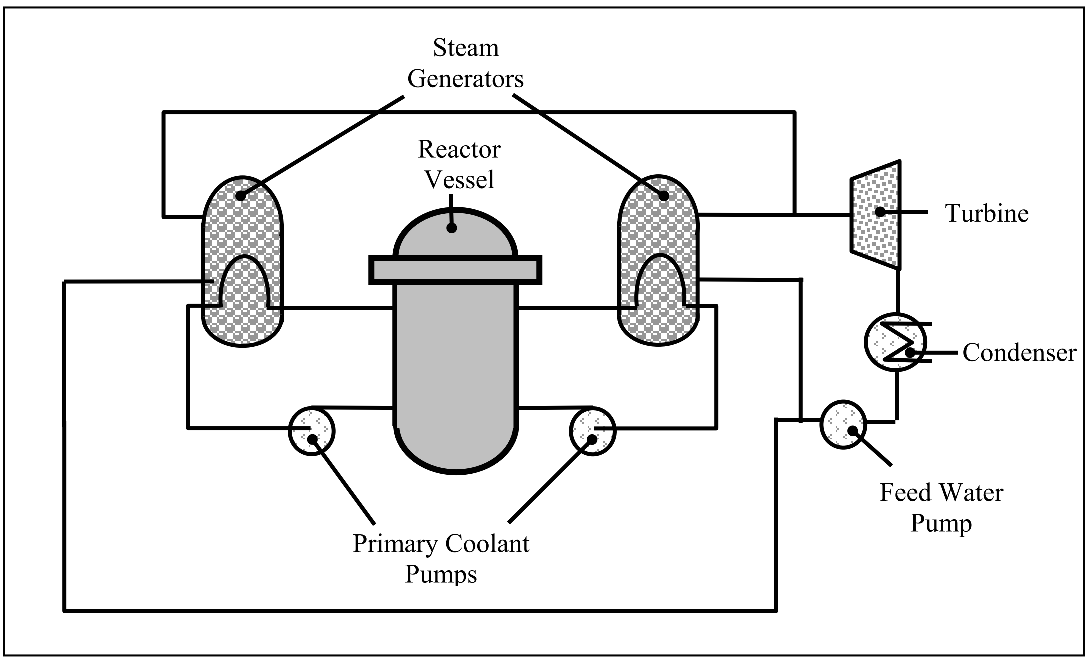


Figure 19. Simplified layout of PWR-design reactor

As was mentioned above, safety is a critical issue for a nuclear power plant. Further, maintenance decisions have an effect upon safety. Therefore it is imperative that maintenance allocation decisions made for the sake of profitability not adversely impact safety. This consideration is not included in the prototype model, but it is included within SAFE-M in order for that model to be useful for real plants (see the following section “Safety Module” for details).

In order to incorporate safety-related constraints into SAFE-M it was necessary to have a suitable measure of the safety of a plant. The model uses CDF as a measure of safety. According to the NRC glossary “CDF is an expression of the likelihood that, given the way a reactor is designed and operated, an accident could cause the fuel in the reactor to be damaged” (NRC website). Thus CDF is considered beyond its purely economic consequences, which would be incorporated as discussed in the preceding subsection.

Core damage can occur as the end result in a number of credible scenarios. An initiating event might be the failure of one or more system components.

The PRA methodology is used by the model to calculate CDF value as a function of maintenance allocations (see section “Safety Module” below for details).

Figure 20 below shows the scheme of SAFE-M.

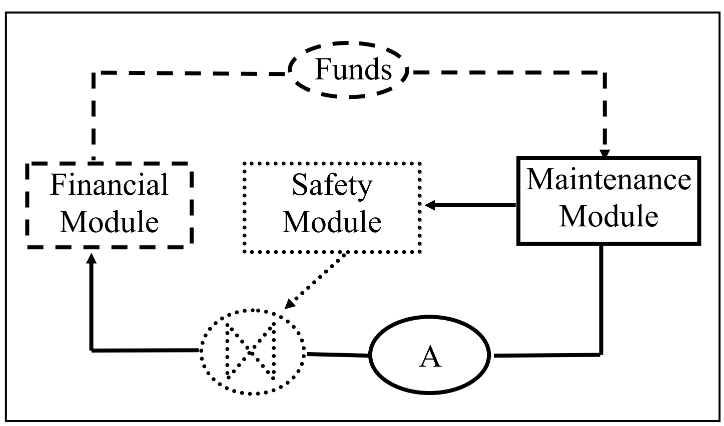


Figure 20. Schematic of the SAFE-M model ("A" stands for availability)

The basic difference between the prototype model scheme and Figure 20 is in the presence of so-called "Safety Module" and the control gate (the valve-shaped object in Figure 20). The safety module will take as input the component-wise failure rates (from the maintenance module), and determine from them the value of CDF which is then to be compared with the prescribed limits in the control gate. If the prescribed limits on the CDF are violated, under the total and component-wise maintenance allocations considered, then the extent of this violation will be reported. This then will be reported to the maintenance module, which will then select the next most economically beneficial use of the allocated maintenance funds, and so on until a use of the maintenance funds has been determined that will not violate the imposed safety constraints.

Also in the prototype model, failure of any system component leads to plant shut down. In other words the plant has only two states: *fully operational* and *shut down.* In reality the situation is more complex. In fact failure can lead to one of the four states:

- no simultaneous effect on system work;
- plant power reduction;
- plant shut down; or
- core damage.

In the case where a component failure does not directly impact the performance of the whole system, it is possible that it will cause a change in the value of core damage frequency (CDF). This would happen from the so-called safety components, i.e. the emergency cooling system for example.

In the SAFE-M model the four states of a plant listed above are taken into account. This permits a more subtle and accurate inclusion within the financial model of the effect upon plant profitability of component failure (see section "Maintenance Module" below for details).

Mathematically the optimization problem for SAFE-M can be stated as follow. The objective function is

$$CF_i = f(M_{i11}, M_{i12}, \cdots, M_{i1K}, M_{i21}, \cdots, M_{i2K}, \ldots, M_{iJ1}, \ldots, M_{iJK}) \tag{16}$$

where CF_i is capacity factor in i^{th} year, and M_{ijk} is the maintenance allocation to the k^{th} ($1 \le k \le K$) maintenance activity of the j^{th} system component in the i^{th} year.

The constraints on the control parameters M_{ijk} are

$$0 \le M_{ijk} < \infty, \text{ for all } i, j \text{ and } k,$$

$$\sum_j \sum_k M_{ijk} = M_i \text{ , for all } i \tag{17}$$

and

$$CDF(M_i) \le CDF_{reqd} \text{ , for all } i$$

where CDF_{reqd} is the value of CDF required by regulations (NUREG 1.174). The objective is to choose the M_{ijk}, subject to the above constraints, to maximize CF_i. (If one chooses, the latter constraint can be replaced by even more stringent requirements; for example that the CDF not be greater than in the previous year, with of course the understanding that in the initial year the CDF must not exceed that permitted by regulatory standards.)

The main question here was how to connect CDF to maintenance allocations. The following approach to solve that is used in the model. The so-called "Work-cost-benefit" table in the format shown below was created and used in the model (see Appendix A for particular examples of this table).

Such a table connects maintenance cost to component failure rate. The knowledge of failure rate for each system components allows us to calculate the probability of system failure (or CDF) using the event tree methodology (see the "Safety Module" section for details). This table is also being used by the maintenance module to define the priority for funds allocation (using increment of benefit per dollar allocated to each system component, see the "Maintenance Module" section for details).

Table 1. Work-cost-benefit table

Component	**W**ork	**C**ost, $	**B**enefit: Δ(Failure Rate)
1	Work 1: replacement		
	⋮		
	Work K		
⋮			
N	Work 1: replacement		
	⋮		
	Work K		

The SAFE-M model again as the prototype model utilizes the iterative feasible direction method for optimization from funds allocation. But, now at each iteration step the model also looks at the safety constraint of the problem. Other words consideration is given to implementing the profit-optimization segment of the maintenance assignment in a manner that ensures the constraints on the CDF are satisfied, if that is possible under the prescribed total maintenance allocation.

Maintenance Module

As was mentioned above the model uses the four-loop PWR system. Such a system consists of four primary loops and one secondary loop. Each of the primary loops has its own steam generator and primary coolant pump. Also since the reactor coolant that flows inside the loops is going through the reactor vessel, a failure of the vessel would affect all four primary loops. The same holds for the pressurizer; failure of that component would affect pressure in the whole system. Therefore, each of the primary loops was modeled in the model in such a way that to take into account all of the mentioned above

$$Primary\ Loop_i : RV, SG_i, PCP_i, PRE, \quad i \in [1,4]$$

where *RV* stands for reactor vessel

SG – steam generator,

PCP – primary coolant pump, and

PRE – pressurizer.

The secondary loop includes such components as turbine (*TUR*), condenser (*CON*), and feed water pump (*FWP*).

The system is one hundred percent available when all four primary loops and the secondary loop are available to perform their designed functions. Another words the system is unavailable when all four of the primary loops fail or the secondary loop fails. Each of the primary loops contributes one fourth (1/4) to the system unavailability.

The parameter that characterizes system availability in the model is capacity factor. Thus the system capacity factor can be expressed as

$$CF = \left[1 - \frac{1}{4}\sum_{i=1}^{4}(U_{PL})_i\right] \cdot \left[1 - U_{SL}\right] \tag{18}$$

where $(U_{PL})_I$ is unavailability of i^{th} primary loop,

U_{SL} – is unavailability of the secondary loop.

Since the equipment can be only in two stages: it is either available or not, its unavailability can be expressed in terms of its availability as

$$(U_{PL})_i = 1 - (A_{PL})_i \tag{19}$$

where $(A_{PL})_i$ is availability of i^{th} primary loop.

Each of the primary loops consists of four components. Failure of any one of those components would cause failure of the whole loop. Thus, a primary loop can be defined as a system of four components in series. Availability of such system would be

$$(A_{PL})_i = \prod_{j=1}^{4} (A_{PL})_{i,j} = \prod_{j=1}^{4} (1 - (U_{PL})_{i,j}) \tag{20}$$

where $(A_{PL})_{i,j}$ means availability of j^{th} component of i^{th} primary loop.

Component unavailability is characterized by its *Mean-Time-To-Repair (MTTR)* and thus can be expressed as

$$(U_{PL})_{i,j} = \frac{MTTR_{i,j}}{MTTR_{i,j} + MTBF_{i,j}} \tag{21}$$

where $MTBF_{i,j}$ stands for *Mean-Time-Between-Failures* of the j^{th} component of the i^{th} primary loop,

$$MTBF_{i,j} = \frac{1}{FR_{i,j}}, \tag{22}$$

where $FR_{i,j}$ is *Failure Rate* of j^{th} component of i^{th} primary loop.

Thus, availability of a primary loop can be expressed as

$$
\begin{aligned}
(A_{PL})_i = \prod_{j=1}^{4}(A_{PL})_{i,j} &= \prod_{j=1}^{4}(1-(U_{PL})_{i,j}) \\
&= \prod_{j=1}^{4}\left[1-\frac{MTTR_{i,j}}{MTTR_{i,j}+MTBF_{i,j}}\right] \\
&= \prod_{j=1}^{4}\frac{MTBF_{i,j}}{MTTR_{i,j}+MTBF_{i,j}} \\
&= \prod_{j=1}^{4}\frac{1/FR_{i,j}}{MTTR_{i,j}+1/FR_{i,j}} \\
&= \prod_{j=1}^{4}\frac{1}{MTTR_{i,j}\cdot FR_{i,j}+1}
\end{aligned}
\tag{23}
$$

Similar considerations for secondary loop components give the following expression for availability of the secondary loop

$$
A_{SL} = \prod_{k=1}^{3}\frac{1}{MTTR_k \cdot FR_k + 1} \tag{24}
$$

Finally system capacity factor can be calculated as

$$
CF = \left\{1-\frac{1}{4}\sum_{i=1}^{4}\left[1-\prod_{j=1}^{4}\frac{1}{MTTR_{i,j}\cdot FR_{i,j}+1}\right]\right\}\cdot\prod_{k=1}^{3}\frac{1}{MTTR_k\cdot FR_k+1} \tag{25}
$$

Sections “Flow Chart” and “Corrective Maintenance” below in the manuscript detail where *MTTRs* and FR_s come from to feed this formula.

Safety Module

During normal operation of a nuclear reactor heat is produced within nuclear fuel in the reactor core (due to fission process). The reactor core is located inside the reactor vessel (RV) (Figure 19). The core is cooled by water, pumped by primary coolant pumps (PCP). Going through the reactor core heats the water (thus “cold” water is coming in the reactor core and “hot” water is coming out). Then the “hot” water goes to steam generators (SG) where it flows inside steam generator tubes; outside these tubes there is cold water of the secondary loop. After the steam generators the primary coolant goes to reactor core again through primary coolant pumps. Steam produced within steam generators is directed to the turbine (TUR) where some part of its energy is converted to electricity. After the turbine the steam is collected in the condenser (CON) where it becomes water again and is pumped back to the steam generators by the feed water pump (FWP).

As it was mentioned above the model works with a four-loop system (i.e., there are four primary loops; each includes one primary coolant pump and one steam generator). One of the four loops includes pressurizer (PRES). The pressurizer is a component by which the system maintains pressure inside the primary loops. All four primary loops have to work during normal operation. The fission process can be stopped by inserting control rods (CR) into the core; however the reactor will still produce some power (due to the decay heat in the fission products). In case of primary coolant pumps failure (all four), there is an emergency cooling system (ECS) with sufficient cooling capability to remove decay heat.

Thus the components in the model can be divided into two groups: non-safety related components (PCP, SG, RV, TUR, CON, PRES, and FWP) and safety related components (CR, ECS). Failure of any non-safety related component leads to an accident situation. Some of these accidents could result in reactor’s core melting (when heat production in reactor exceeds its cooling).

There are two possible situations when the core can melt:

1. Reactor operates at normal power and cooling is less then that at normal conditions.
2. When reactor produces the decay heat and there is no cooling at all.

This is represented graphically in the fault tree in Figure 21.

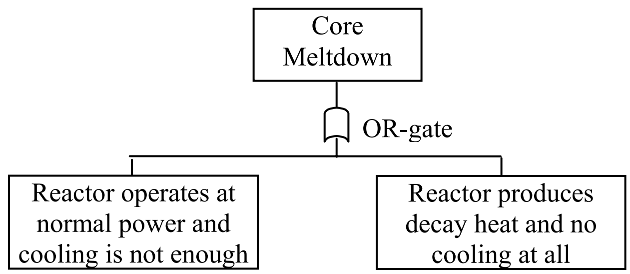


Figure 21. Two cases of core meltdown

Usually if any serious problem is detected with reactor cooling when the reactor is at normal power then the reactor must be shutdown by inserting control rods into the reactor core. If control rods fail to be inserted then this causes the first (in the list above) situation that could lead to reactor core meltdown, depending whether there is enough cooling capability or not.

The cooling in this situation can be not enough in one of the following cases:

- coolant is leaking through the reactor vessel or pressurizer,
- secondary loop has failed, or
- at least one of the primary loops is not available along with some problems with emergency cooling system.

Figure 22 shows fault tree for this case. The circles represent the events with a known failure rate.

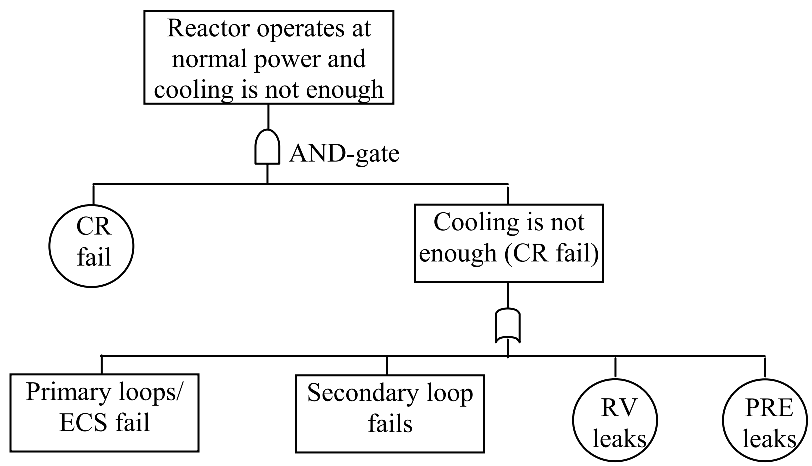


Figure 22. Reactor operates at normal power and cooling is not enough

The “Primary loops/ECS fail” event can happen when either emergency cooling system fails along with failure of one of the primary cooling pumps, or when at least two primary pumps fail. Secondary loop fails when the feed water pump fails.

If control rods have not failed and are inserted into the reactor core then the reactor operates in the so-called decay-heat mode. Power generation during this mode is significantly less then during full power operation but the heat generated still needs to be removed from the core in order to not cause the core meltdown. This heat can be removed by either the emergency cooling system or one of four primary cooling loops, with an assumption that the secondary loop is in an operable condition. Since in the decay heat mode the reactor core could be cooled by reduced amount of coolant, it is assumed here that the reactor would deal safely with leakage (if any) of reactor vessel or pressurizer while it is in the decay-heat mode (we are talking here about small leakages of reactor vessel or pressurizer only, not their rupture that). Figure 23 shows fault tree for this case.

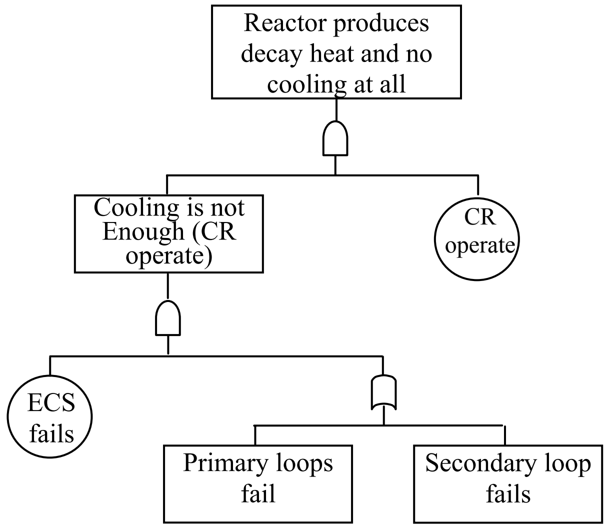


Figure 23. Reactor produces decay heat and no cooling at all

Here primary loops fail when all four of the loops fail, and again secondary loop fails when feed water pump fails.

Figure 24 shows the combined fault tree for core meltdown event.

Failure of turbine or condenser does not affect secondary water circulation but increases temperature of water entering the feed water pump, resulting in increasing of its (feed water pump) failure probability. It is assumed in the model that feed water pump failure probability is increased by a factor of two in case of the turbine or condenser failure. Similarly, failure of a steam generator doubles the probability of turbine failure because in this case primary water will leak to the turbine.

In the real world failure rate of a component could be controlled by means of monitoring and maintenance.

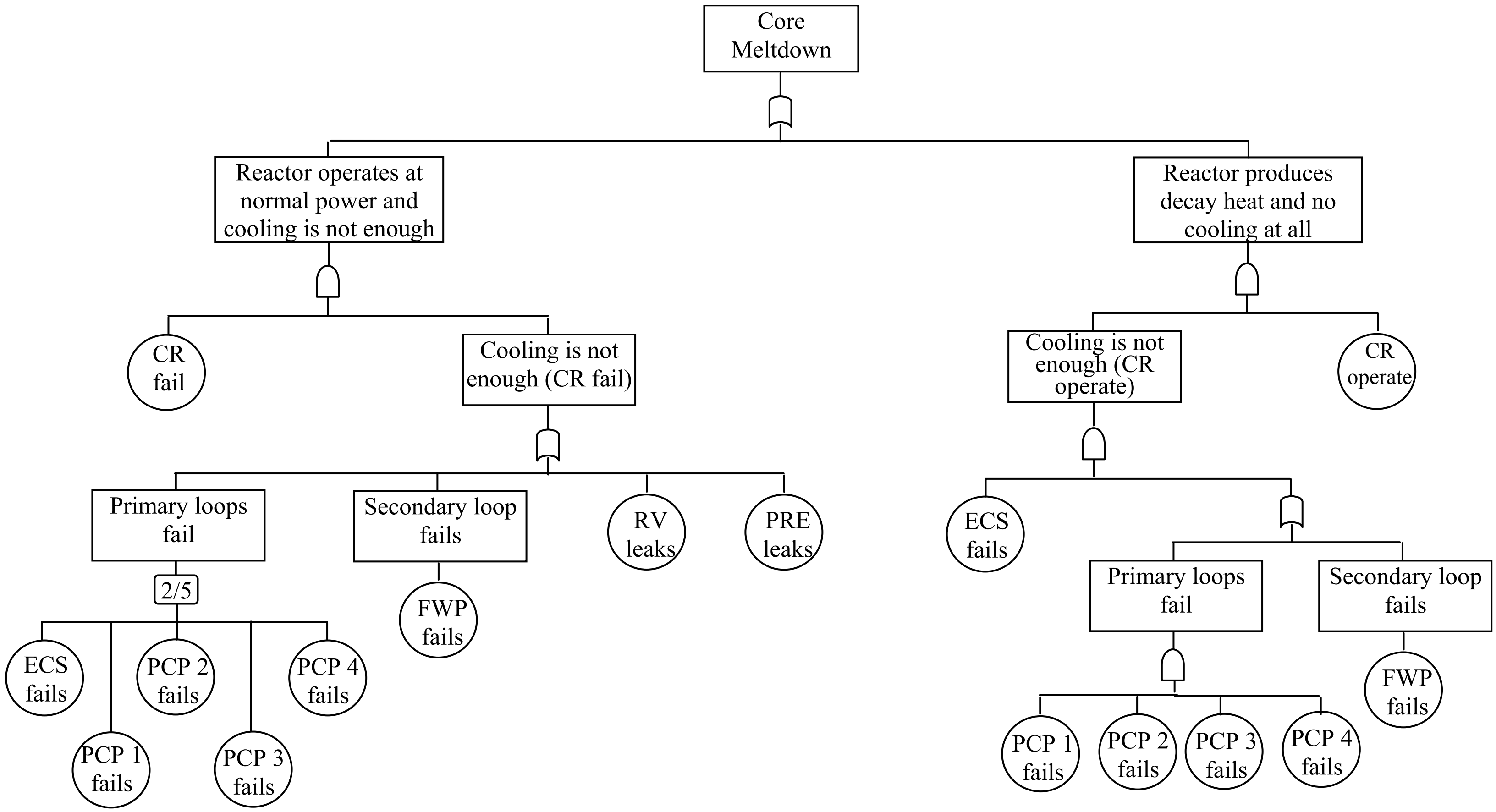


Figure 24. Fault tree for the SAFE-M model

In order to be able to analyze such a system for possible safety problems (core meltdown) one needs to think about possible scenarios that can lead to the core meltdown process. As it was mentioned above, failure of the turbine or the condenser does not affect the secondary water circulation; also, failure of a steam generator does not affect primary water circulation. Thus, for this particular model the only things that affect water circulation in the reactor, and as a consequence removal of heat from the reactor core, are a failure of a primary cooling pump, or of the feed water pump, or leakage of reactor vessel or pressurizer.

For the reasons described above, the failure rate of the feed water pump can be influenced by either failure of a steam generator, or turbine, or condenser. Each of these failures increases failure rate of the pump. Therefore the failure rate of the pumps can be expressed as

$$FR_{FWP} = \begin{cases} FR_{FWP} & \textit{neither condenser, nor turbine, nor a steam generator fails} \\ FR_{CONDS} \cdot 2 \cdot FR_{FWP} & \textit{condenser fails} \\ FR_{TUR} \cdot 2 \cdot FR_{FWP} & \textit{turbine fails} \\ FR_{SG} \cdot 2 \cdot FR_{TUR} \cdot 2 \cdot FR_{FWP} & \textit{steam generator fails} \end{cases}$$

Using formula of total probability

$$\left(FR_{FWP}\right)_{tot} = FR_{FWP} + FR_{TUR} \cdot 2 \cdot FR_{FWP} + FR_{SG} \cdot 2 \cdot FR_{TUR} \cdot 2 \cdot FR_{FWP} + FR_{CONDS} \cdot 2 \cdot FR_{FWP} \quad (26)$$

As was also mentioned above only a failure of a primary cooling pump, the feed water pump, or leakage of reactor vessel or pressurizer influences the cooling circulation. Thus we need to calculate the probability for the core to meltdown when any one of these components fails. To perform such calculation Precision Tree software (from Palisade Decision Tools Suit) was used.

During the analysis it was assumed that all four primary cooling pumps are completely identical (i.e., impact the same way the reactor work). Figure 25 - Figure 28 show constructed event trees for the failure of any one of the primary coolant pumps. The trees differ from each other only by initial event (i.e., from the failure of which one primary pumps the tree is growing). The trees should be read from the left to the right starting from tree's name and initiating event. After tree is built its branches are evaluated automatically by the software.

If one of the primary pumps fails then the first event supposed to happen after that is shutting down the fission reaction by inserting control rods into the reactor core. If the control rods fail then the reactor could still operate safely at full power if all other primary loops and the secondary loop are available and the ECS compensates for the loss of the primary loop. If control rods respond to the loss of one primary loop, then the power generated in the reactor core is due to decay process in nuclear material only, and for safely cooling the reactor it is enough to have in operable condition either one of the remaining three primary loops and the secondary loop, or (if remaining primary loops or secondary loop fail) the emergency cooling system.

Figure 29 shows the event tree for feed water pump failure. If the feed water pump fails then again the reactor must be shutdown by inserting control rods into the reactor core. If control rods fail then this becomes a situation when the reactor is at full power and cooling is not enough, which leads to reactor core meltdown. If the control rods operate but the emergency cooling system fails then this is the situation when the reactor produces decay heat and no cooling at all, and this again will lead to the reactor core meltdown.

Figure 30 shows event tree for reactor vessel failure (leakage). When the reactor vessel leaks then the primary coolant inventory is decreasing. Again the reactor must be shut down using the control rods. If the control rods operate then the reactor is transferred into the decay-heat mode and it is enough to have the emergency coolant system available for the reactor to be safely cooled. If control rods fail or emergency cooling system is not available (when control rods are available) that leads to the reactor core meltdown.

Figure 31 shows the event tree for pressurizer failure. In case of the pressurizer leakage we again have the situation with decreasing inventory of the primary coolant (as in the case of reactor vessel leakage just described), so the exact same considerations hold.

Each branch of the event trees in Figure 25- Figure 31 leads either to reactor core meltdown (“FR meltdown”) or to be safely cooled (“FR OK”). Then for each of the trees the meltdown branches are summed up calculating thus the probability of core meltdown when a component fails. By summing up then these values (one for each tree) the total probability of reactor core meltdown is calculated (these calculations are done in the safety module).

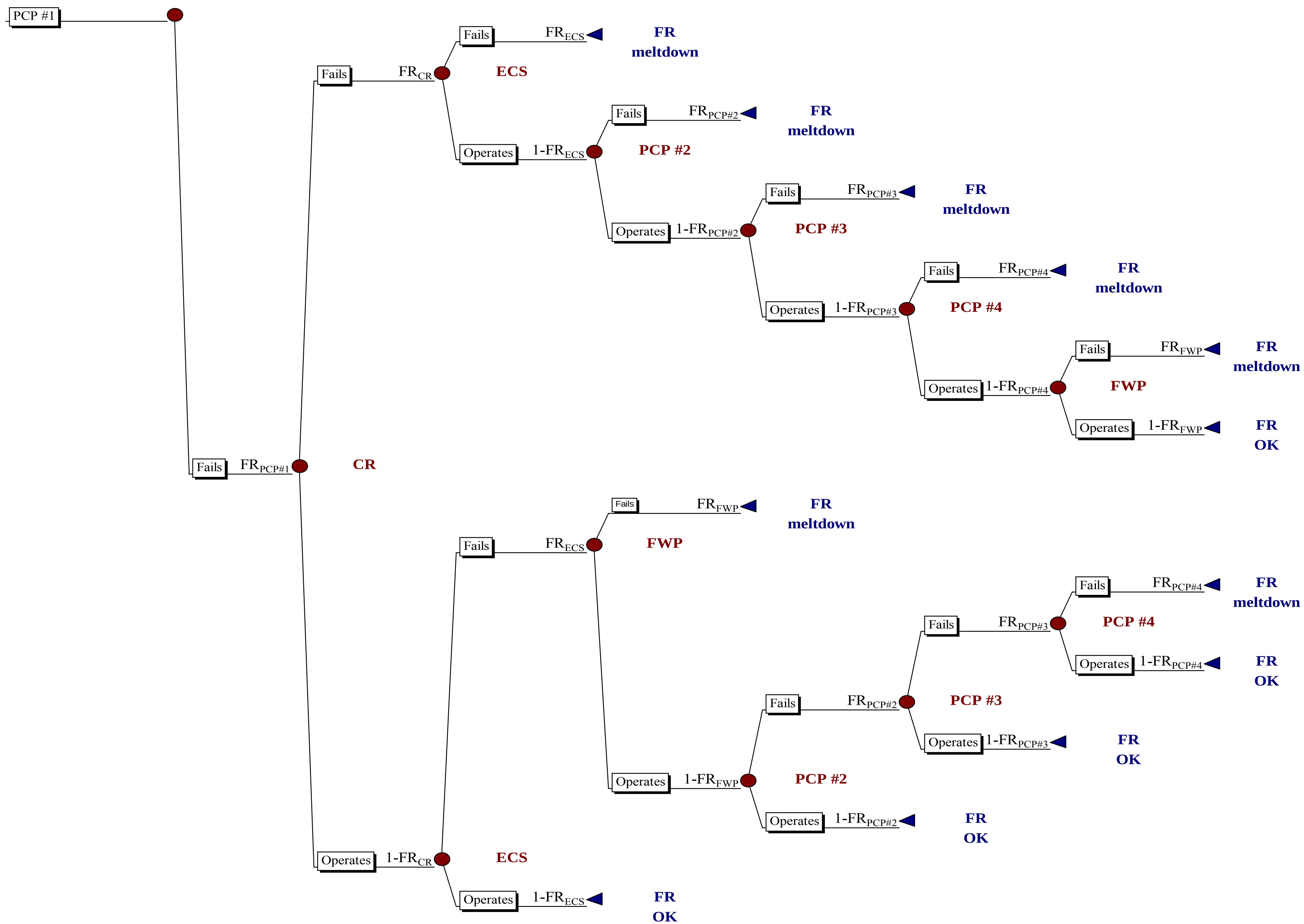


Figure 25. Event tree for PCP #1 failure

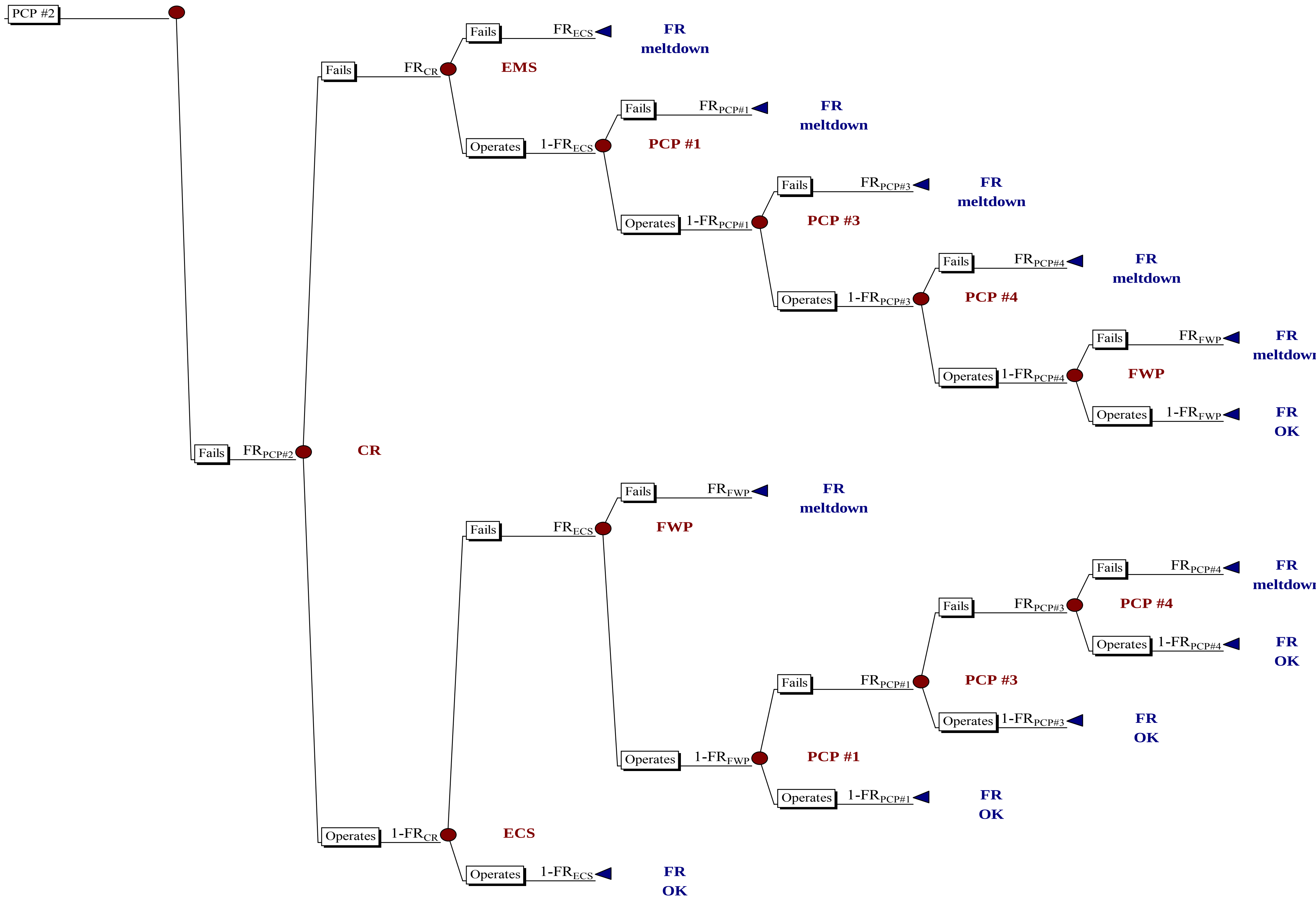


Figure 26. Event tree for PCP #2 failure

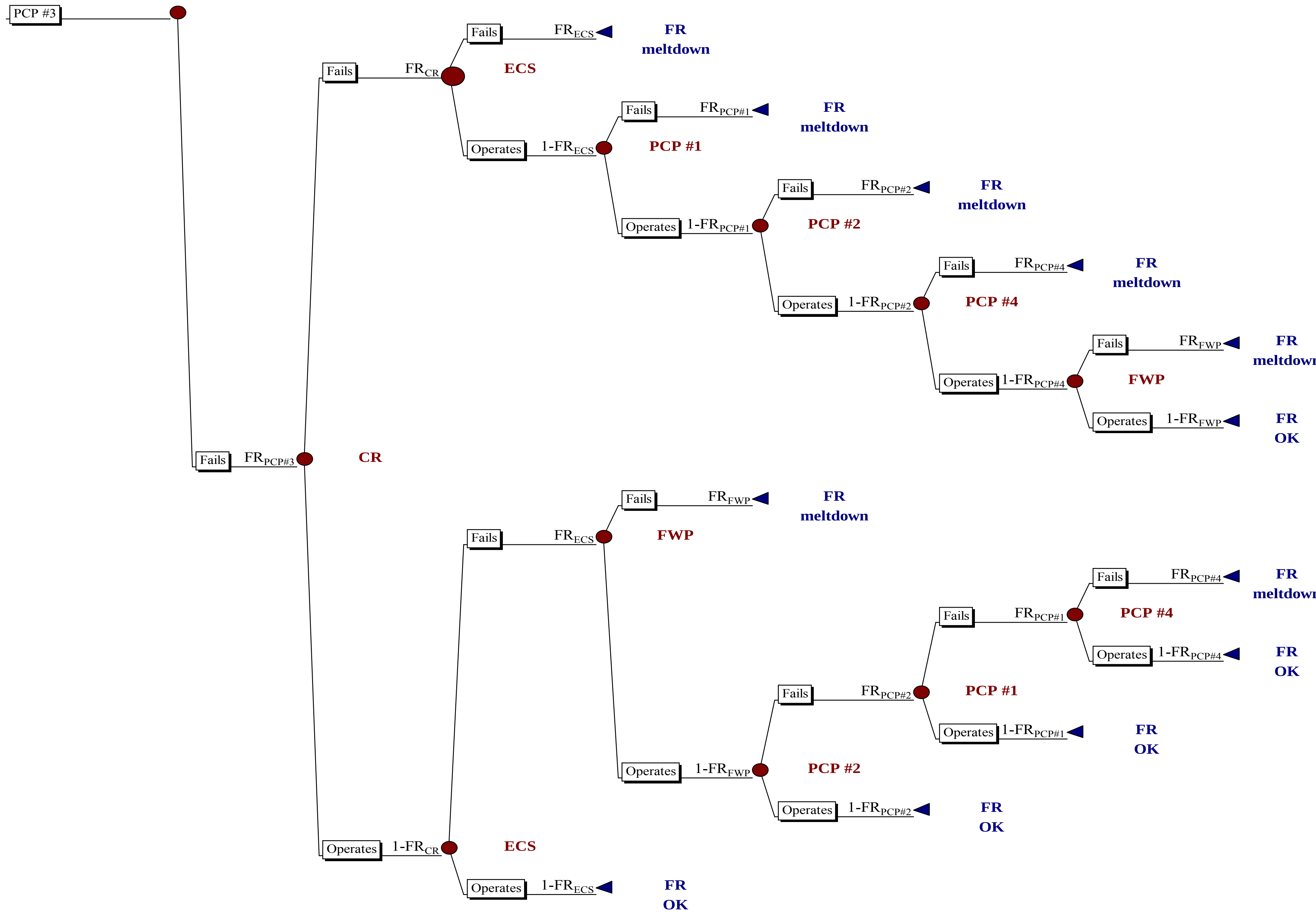


Figure 27. Event tree for PCP #3 failure

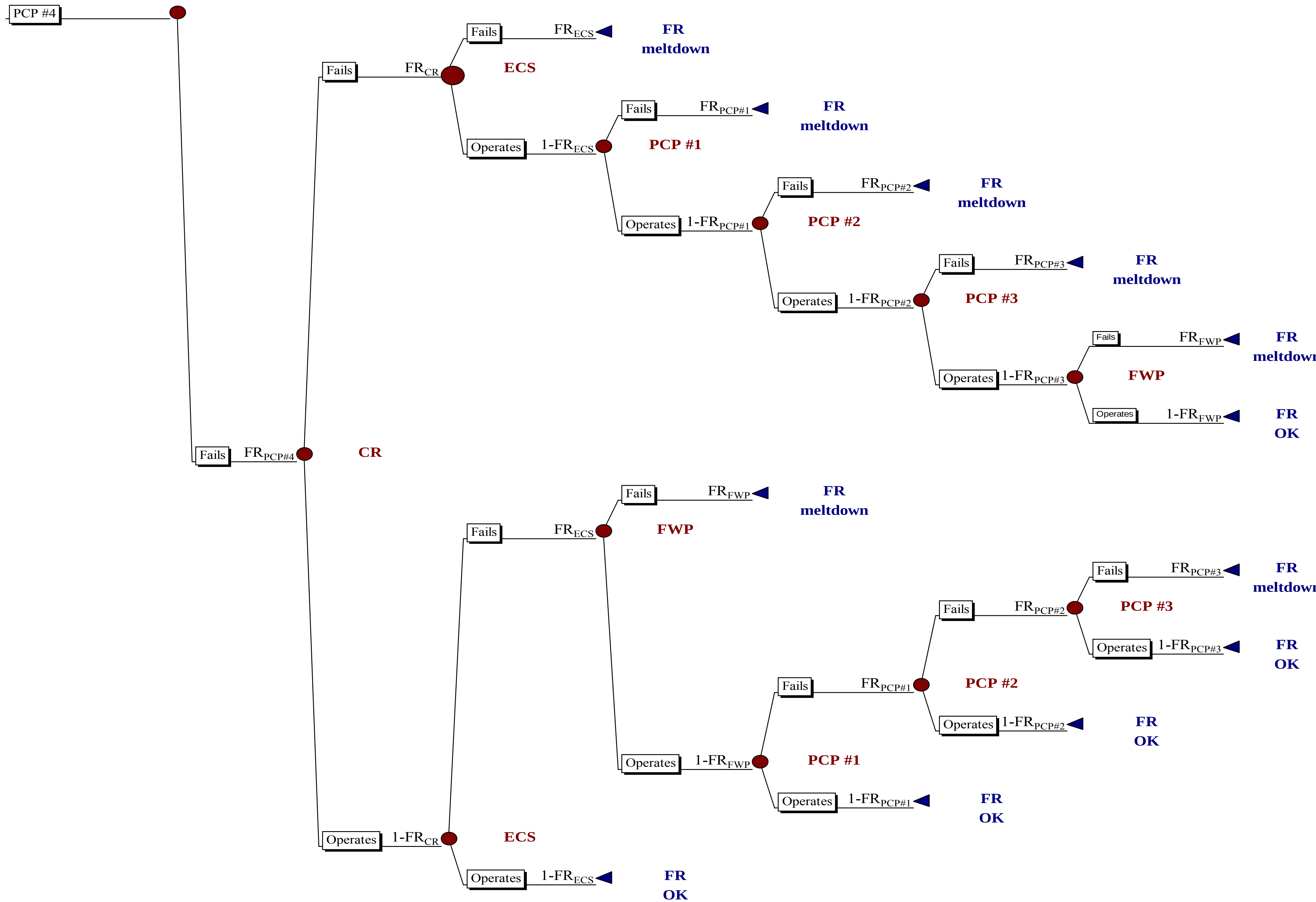


Figure 28. Event tree for PCP #4 failure

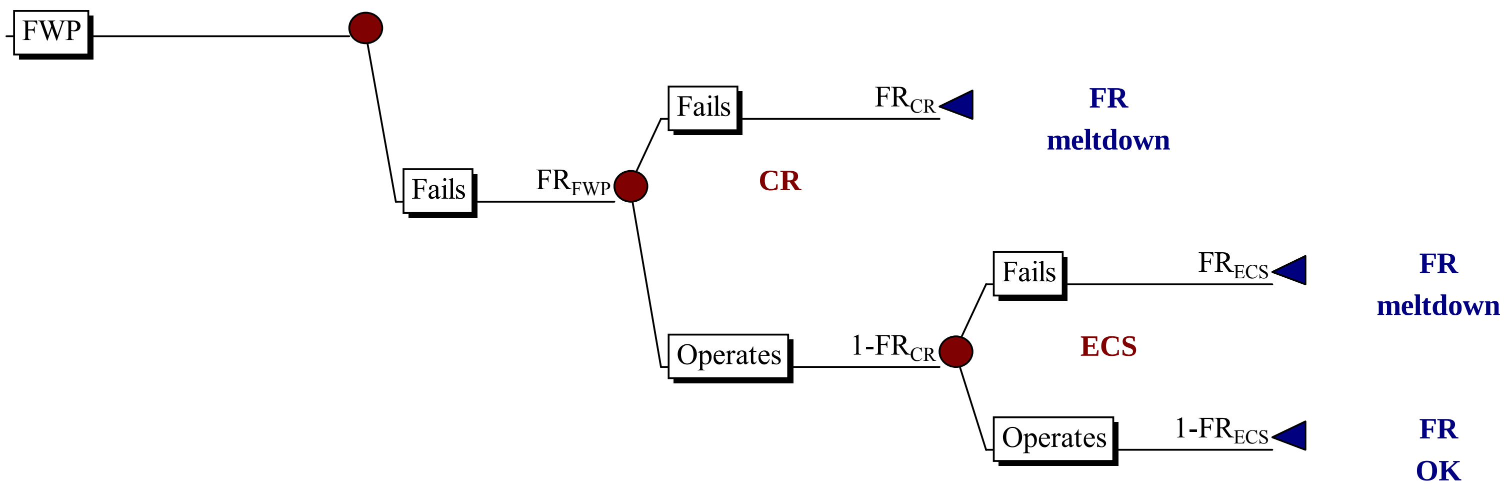


Figure 29. Event tree for FWP failure

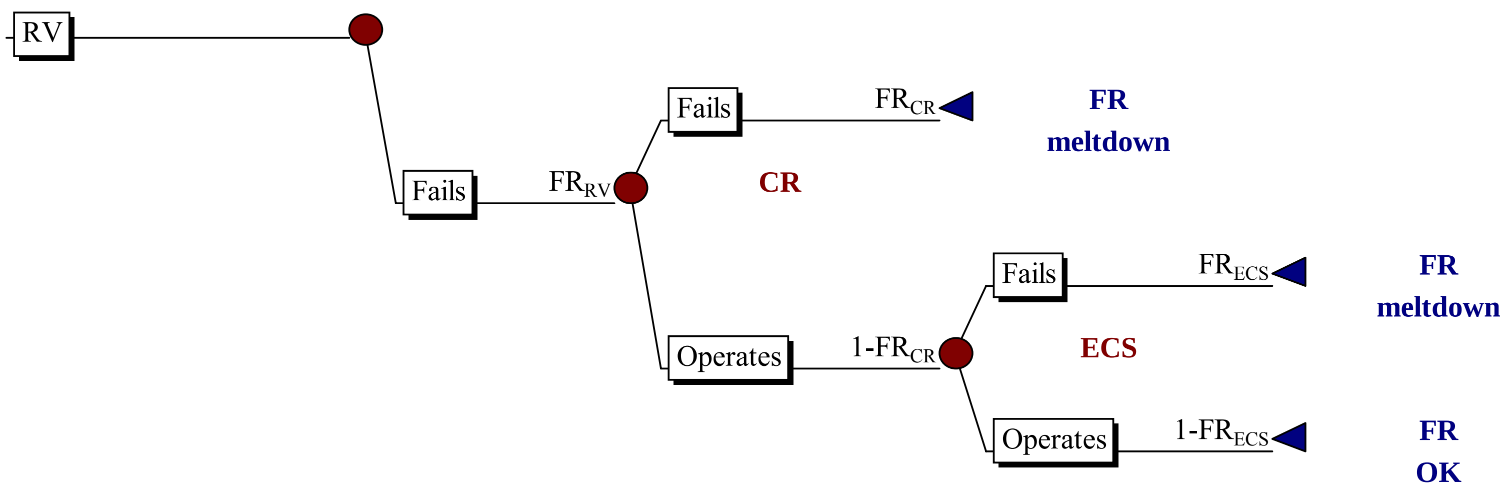


Figure 30. Event tree for RV failure

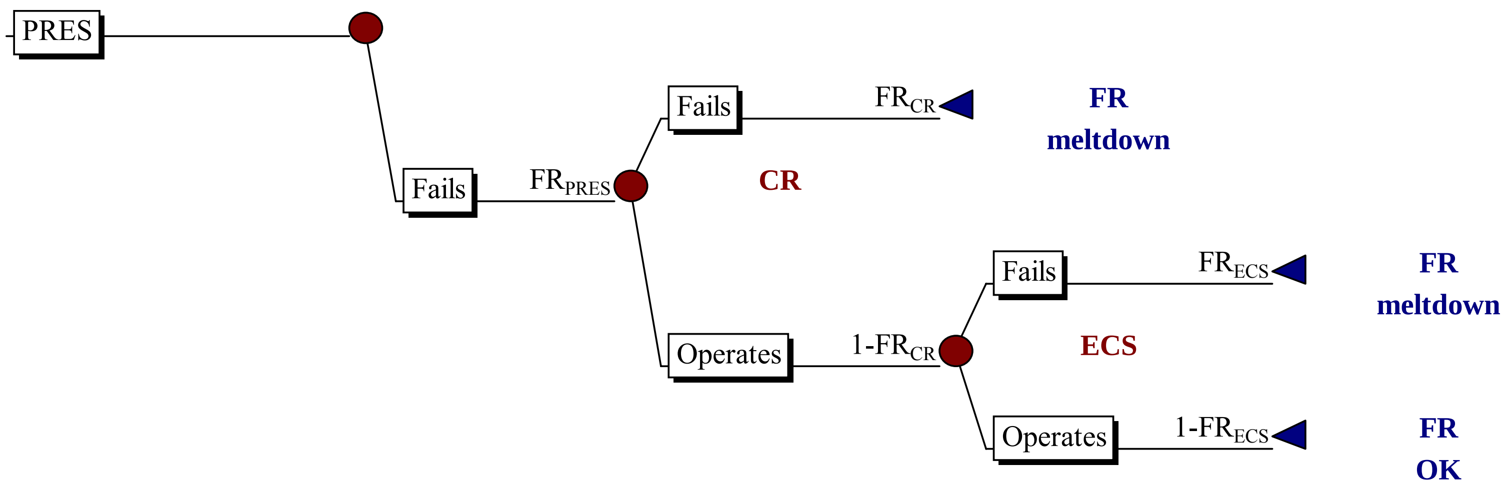


Figure 31. Event tree for PRES failure

Financial Module

Introduction

This module runs full expense analysis and produces standard financial statement; e.g., income statement, statement of cash flows (Sullivan, 2003).

Revenues

Most nuclear plant revenue comes from sales of electricity. This model works with four types of customers for the sales:

- residential sales,
- commercial sales,
- industrial sales, and
- public street lighting sales.

For each of these four groups of customers the model also has two additional parameters:

- percent of electricity sold, and
- price of electricity sold, \$/kWt.

Then the quantity of electricity sold to each of customers is defined as

$$(N_{elec})_i = (Percent\ of\ electricity\ sold)_i \cdot Plant\ Capacity \cdot Capacity\ Factor \qquad (27)$$

And the revenue received from i-th customer is

$$Revenue_i = (N_{elec})_i \cdot (Price\ of\ electricity\ sold)_i \qquad (28)$$

The total revenue form the electricity sales is

$$Revenue_{tot} = \sum_i Revenue_i \tag{29}$$

This value is used in the model as net sales. If the revenues received under each rate are not issues for the study then the net sales could be found as

$$Net\ Sales = Electricity\ Price \cdot Plant\ Capacity \cdot Capacity\ Factor \tag{30}$$

where

$$Electricity\ Price = \sum_i (Type\ of\ \ customers)_i \cdot Price_i \tag{31}$$

Expenses

The model takes into account only major groups of expenses as described below.

- Maintenance Expenses

In the real world every engineering system requires some attention from time to time. If it breaks it needs to be repaired (so-called corrective maintenance). Also some work might be done on the working system in order to eliminate its future failures (this type of maintenance is called preventive). Both of these types of maintenance require money to be spent and thus must be accounted for in the financial statement.),

- Fuel Expenses

The model uses refueling cycle of 18 months and 27 days as the duration of the refueling outages.

$$Fuel\ Expenses = N_{ass} \cdot C_{ass} \cdot f_{ass} \tag{32}$$

where

N_{ass} – number of fuel assemblies in the core,

C_{ass} – cost per fuel assembly,

f_{ass} – fraction of fuel assemblies replaced during refueling outage.

- Power Generation Expenses without Fuel and Maintenance

This category of expenses includes:

- Coolants and Water
- Electric expenses
- Operation Supervision and Engineering
- Steam expenses
- Miscellaneous nuclear power expenses

- Administrative and General Expenses (Excluding wages and salaries)

- Employee Benefits and Pensions
- General Advertising Expenses
- Injuries and Damages Reserve
- Insurances Expenses
- Maintenance of Offices
- Miscellaneous General Expenses
- Office Expenses
- Regulatory Commission Expenses
- Rents

- Wages and Salaries

- Executive Salaries
- Administrative Salaries

- Outside Service Expenses

Interest Payments

To return the money that was borrowed to build the plant the model utilizes a system with equal annual payments of compound interest and principal (Sullivan, 2003). Each payment covers accrued interest and a partial amount of principal repayment.

The model also utilizes the end of year convention, which means that "all cash flows are assumed to occur at the end of an interest period. When several receipts and disbursements occur within a given interest period, the net cash flow is assumed to occur at the end of the interest period" (Blank and Tarquin, 2002). With this convention in mind, the annual payments that occur at the end of each period for N periods with $i\%$ is the interest rate per period are

$$A = Capital\ Investment \cdot (A/P, i, N) \tag{33}$$

where $(A/P, I, N)$ is the uniform series capital recovery factor (Sullivan, 2003)

$$(A/P, i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{34}$$

The scheme of calculating the interest and principal reduction payments is following (Sullivan, 2003).

Step 1. Amount owed at beginning of period over which the interest occurs (for the very first period this amount equal to loan), P

Step 2. Interest occurred for the period

$$I = P \cdot i \tag{35}$$

Step 3. Total money owed at end of period

$$F = P + I \tag{36}$$

Step 4. Principal reduction payment

$$PR = A - I \tag{37}$$

Step 5. Amount owed at beginning of the next period

$$P_{next} = P - A \tag{38}$$

Repeat steps *2* - *5* using P_{next} instead of P.

If the calculations are done correctly then at the end of year N

$$\sum_{i=1}^{N} PR_i = P \tag{39}$$

Since the loan balance decreases over time due to the equal end-of-year payments, the interest decreases; at the same time the portion toward principal repayment increases over years.

Depreciation

“The capital investments of a corporation in tangible assets – equipment, computers, vehicles, buildings, and machinery – are commonly recovered on the books of the corporation through depreciation. Although the depreciation amount is not an actual cash flow the process of depreciating an asset (also referred as capital recovery) accounts for the decrease in an asset's value because of age, wear, and obsolescence. Even though an asset may be in excellent working condition, the fact that it is worth less through time is taken into account in economic evaluation studies" (Blank and Tarquin, 2002).

The depreciation is important to engineering economy because it is a tax-allowed deduction included in tax calculations. Depreciation lowers income taxes via the relation (Blank and Tarquin, 2002)

$$Taxes = (Income - Deductions) \cdot (Tax\ Rate)\ . \tag{40}$$

The Modified Accelerated Cost Recovery System (MACRS) created by the Tax Reform Act of 1986 (TRA 86) is now the principal method for computing depreciation deduction for property in engineering projects (Sullivan, 2003). The MACRS can be applied to both types of property: personal and real. Personal property is the income-producing, tangible possessions of a corporation used to conduct business (vehicles, manufacturing equipment, computers and networking equipment, and much more). Real property includes real estate and all improvements – office buildings, manufacturing structures, test facilities and other structures. Land itself is considered real property, but it is not depreciable (Blank and Tarquin, 2002).

For the purpose of this study the only real property is considered for the depreciation deductions. For real property, MACRS utilizes the straight line method (a constant amount is depreciated each year) for n = 39 throughout the recovery period (depreciable life n of the asset, in years) (Blank and Tarquin, 2002). The annual percentage depreciation rate is $d = 1/39 = 0.02564$. However, MACRS forces partial-year recovery in years 1 and 40. The MACRS real property rates in percentage amounts are

Year 1	$100d_1 = 1.391\%$
Year 2-39	$100d_t = 2.564\%$

Year 40 $100d_{40} = 1.177\%$

And the depreciation amount in year k is defined as

$$D_k = B \cdot d_k \tag{41}$$

where B is cost basis (the initial cost of acquiring an asset defined as purchase price plus any sales taxes, including transportation expenses and other normal costs of making the asset serviceable for its intended use), including allowable adjustments.

The MACRS depreciation rates are presented for 1 year longer than the stated recovery period. Also the extra-year rate is approximately one-half of the previous year's rate. This is because a built-in half-year convention is imposed by MACRS. This convention assumes that all property is placed in service at the midpoint of the tax year of installation. Therefore, only about 50% of the first-year depreciation applies for tax purposes. This removes some of the accelerated depreciation advantage and requires that the rest of the depreciation be takes in year $n + 1$. Salvage value is defined to be 0 under MACRS.

Taxes

The transfer from estimating cash flow before taxes to cash flow after taxes involves a consideration of significant tax effects that may alter the final decision, as well as estimate the magnitude of the tax effect on cash flow over the life of the project.

At the end of each tax year, a corporation must calculate its net (i.e., taxable) before-tax income or loss. Several steps are involved in this process, beginning with the calculation of *gross income* (the total income realized from all revenue-producing sources of the corporation, plus any income from other sources such as sale of assets, royalties, and license fees) (Sullivan, 2003). The corporation may deduct from gross income all ordinary and necessary operating expenses, including interest, to conduct the business, except capital investments. Deductions for depreciation are permitted each tax period as a means of consistently and systematically recovering capital investment. Consequently, allowable expenses and deductions may be used to determine taxable income:

$$\begin{aligned}\text{Taxable Income} = \text{Gross Income} - \text{All Expenses Except Capital Investment} \\ \text{- Depreciation Deductions}\end{aligned} \tag{42}$$

Interest (on the capital investment loan) occurred during a tax period is tax deductible, thus it is treated as an expense for this period.

This taxable income is also referred to as *net income before tax (NIBT)*. When income taxes (assessed as a function of taxable income) and not tax deductible cash flows (principal reduction payments on the loan for initial investment) are subtracted the remainder is called the net income after taxes (NIAT). In summary,

$$\text{Net Income After Taxes} = \begin{Bmatrix}\text{Taxable Income} \\ \text{(i.e., NIBT}\end{Bmatrix} - \text{Income Taxes} - \begin{Bmatrix}\text{Non-Tax Related} \\ \text{Cash Flows}\end{Bmatrix} \tag{43}$$

There are also other taxes that are not directly associated with the income-producing capability of a new project, but they are usually negligible when compared with federal and state income taxes (Sullivan, 2003). The example here can be property taxes. These taxes are assessed as a function of the value of property owned and the applicable tax rates. Hence, they are independent of the income or profit of a project. They are levied by municipal, county, or state governments. This kind of tax is normally deducted from gross income, as any other operating expense would be, in determining the taxable income.

Net Present Value

After the tax analysis for year k is performed and after tax cash flows are determined they are discounted to get net present values (*NPV*) (Sullivan, 2003).

$$(NIAT_{NPV})_k = \frac{NIAT_k}{(1+i)^k} \tag{44}$$

Also such issue as *inflation* must be taken into account. “Inflation is an increase in the amount of money necessary to obtain the same amount of product or service before the inflated price was present. Inflation occurs because the value of the currency has changed – it has gone down in value. The value of money has decreased, and as a result, it takes more dollars for fewer goods. This is a sign of inflation (Blank and Tarquin, 2002).

The present worth calculation adjusted for inflation can be done using the expression

$$\begin{aligned}(NIAT_{NPV})_k &= \frac{NIAT_k}{(1+i)^k} \cdot \frac{1}{(1+f)^k} \\ &= NIAT_k \cdot \frac{1}{(1+i+f+if)^k}\end{aligned} \tag{45}$$

where f is inflation rate.

Sometimes the equation above can be found written as

$$(NIAT_{NPV})_k = NIAT_k \cdot (P/F, i_f, k)\,, \tag{46}$$

where i_f is the inflation-adjusted interest rate and is defined as (Blank and Tarquin, 2002)

$$i_f = i + f + if\,, \tag{47}$$

and *(P/F, i_f, k)* is the single amount present worth factor

$$(P/F, i_f, k) = \frac{1}{(1+i_f)^k}\,. \tag{48}$$

Flow Chart

The SAFE-M model consists of two structural parts: the code file written in Microsoft Visual Basic.Net and the Microsoft Excel file used as the model's input/output file. This section describes the structure and work of the first part of the model – the code.

The code starts its work by reading initial data from the Excel spreadsheet (the complete list of initial data needed by the code to work properly is shown in "SAFE-M Input/Output Structure" section below). Figure 32 shows flow-chart for the SAFE-M model.

The first thing that the code gets from these data are failure rates (FR) for the system components. Then the code calculates initial stage of the system in terms of capacity factor (CF_{in}) and core damage frequency (CDF_{in}). These two parameters correspond to the brain-new system (i.e., all components are new, no aging has appeared yet).

As soon as system starts to operate its components begin to wear-out. The performance of the components (and the system itself as a consequence) decreases. Parameters that show the components performance in the code are their failure rates. Thus, at the next step the code recalculates failure rate for each component with taking into account components aging process (FR_{age}). Those failure rates are used then to calculate capacity factor of the aged system (CF_{before}).

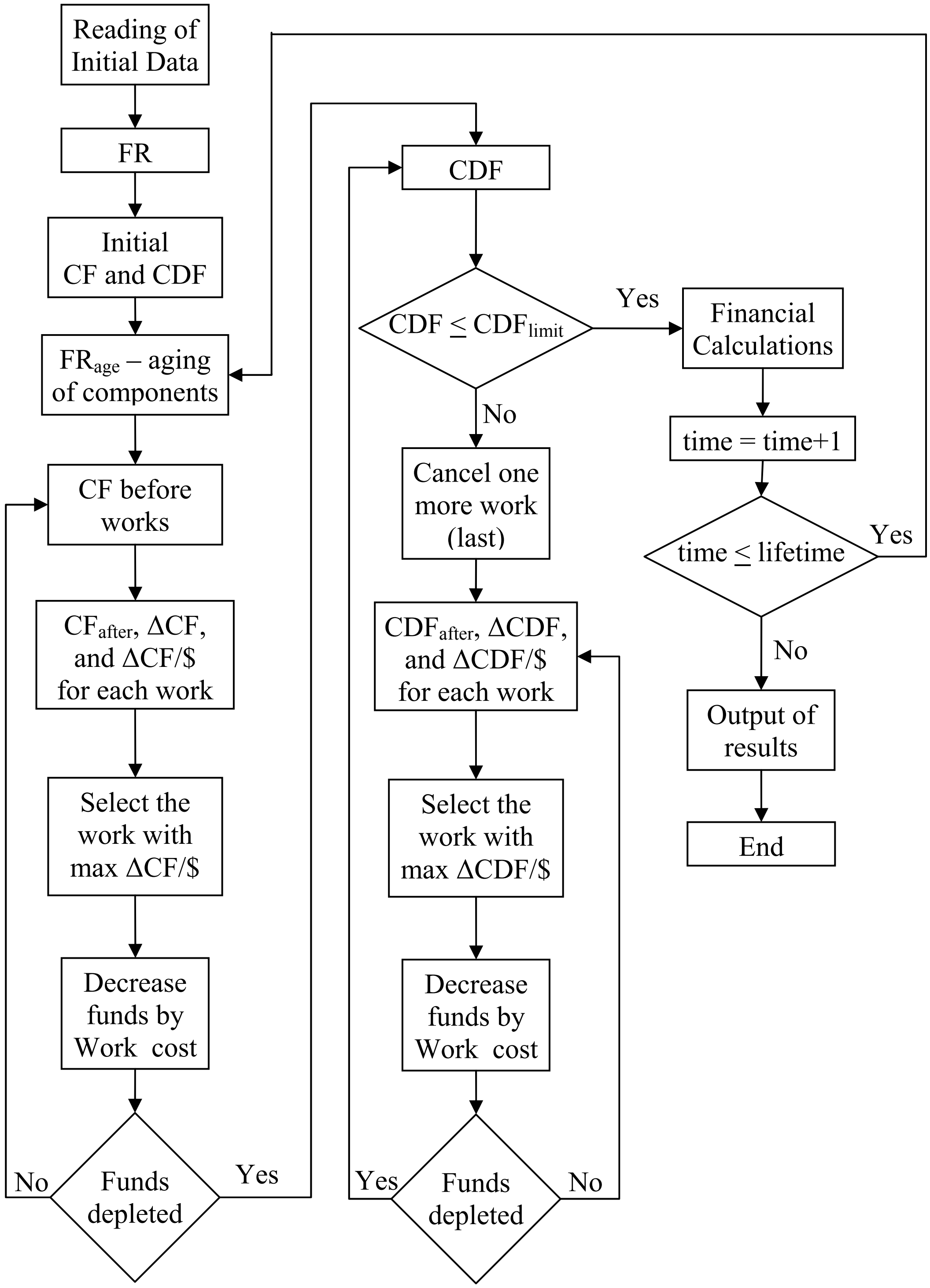


Figure 32. Flow chart of the SAFE-M model

There are two ways to increase performance of aged component in the code: to replace it by a brand-new one, or to repair it (by replacing parts of the component). As a consequence (in most cases) any work done with any one particular component will affect performance of the whole system (system failure rate and capacity factor as a consequence). To take this effect into account the code calculates system capacity factor for each possible work with any one of the system component (CF_{after}). Then the difference between CF_{after} and CF_{before} gives benefit in system capacity factor from any one particular work done with the system components.

Any work costs money and in the real world the available budget is always limited. Thus, to maximize return on money allocated in the system the code calculates the benefit in capacity factor per dollar allocated ($\Delta CF/\$$) and does the work that has maximum value of $\Delta CF/\$$. As it was mentioned above any particular work done affects the whole system. Thus, after work is done the code recalculates CF_{before}, CF_{after}, and $\Delta CF/\$$. The work that has been done will have the same value for CF_{after} and CF_{before}, and as a consequence it will have zero value for $\Delta CF/\$$ (that will eliminate this work from being done again). Then again the code looks for the work that have maximum value of $\Delta CF/\$$ and does the corresponding work. This process is repeated until all available funds are allocated.

After the budget is depleted the code calculates core damage frequency (CDF) for the updated system and compare that value with one defined by the regulations (CDF_{limit}).

If value of CDF does not exceed the regulatory limit then the code performs financial calculations and produces a financial statement for the system for this particular year. After that the new budget for maintenance for the next year becomes available and all the described above starting with recalculating FR_{age} for the system components is repeated.

In case when the model safety constraint is violated (i.e., $CDF > CDF_{limit}$) the following steps are performed by the code to return the system into the permitted limits.

The code cancels the last performed work. That frees some money (in amount that work costed). Now the code calculates CDF_{before}, CDF_{after}, and $\Delta CDF/\$$ for each possible work. Then the work that has largest value of $\Delta CDF/\$$ is found and if the available funds are sufficient to perform this work it is being done. If the budget is not sufficient to do this work then the next to the largest value of $\Delta CDF/\$$ work is found and performed, and so on.

After the work is done the code recalculates CDF_{before}, CDF_{after}, and $\Delta CDF/\$$ for the reasons similar to those explained above in the capacity factor maximization part. Then again, the work with largest value of $\Delta CDF/\$$ and for which funds are available is performed. This process is repeated until all available funds are allocated.

Then the code recalculates the system CDF and compares it again with the regulatory limit. If now the value is in the permitted limits the code performs the financial calculations. If the value still exceeds the limit then the code cancels one more work from the list of works that were done while maximizing system capacity factor. Now money from the last two works performed is freed and the CDF optimization process described above is repeated.

This cycle is repeated until $CDF \leq CDF_{limit}$.

If all the performed works were canceled but CDF still exceeds the permitted limit then it will mean that the available budget is not sufficient to cover system aging; the corresponding message will be generated for a user.

The process described above gives maximum system capacity factor from the available budget and under the safety constraint. The maximum capacity factor is achieved because funds were allocated to works that give maximum benefit in terms of ΔCF/$. Then when the safety constraint was violated the code cancels works starting from the very bottom of the list of works performed (i.e., the works with minimum value of ΔCF/$ compare with any other works performed). The CDF optimization process described above guarantees that the safety constraints are not violated.

Corrective Maintenance

Corrective maintenance is based on the principle: fix it when it breaks. There are at least two possible ways to take into account costs of this type of maintenance: (1) based on the expected number of failures and expected cost to repair, and (2) the simulation-based method. Both of these ways are available in the model (to choose one or another a user will need to select the respective option button).

In the first method, for one to be able to take into account corrective maintenance it is needed to estimate number of failures first. Number of failures for i^{th} component over time T can be expressed in terms of its failure rate (FR) as

$$(Number\ of\ \ failures)_i = FR_i \cdot T \tag{49}$$

Then estimated expenses to fix these failures are

$$Expenses_i = (Number\ of\ \ failures)_i \cdot MCTR_i \tag{50}$$

where $MCTR_i$ is Mean-Cost-To-Repair for i^{th} component.

And the expected expenses for corrective maintenance for whole system will be

$$Corrective\ Maintenance\ Expenses = \sum_i Expenses_i \qquad (51)$$

Even if one knows the failure rate of a component, and thus its probability to failure, he or she does not know for sure if the component will fail or not. To simulate this real-life uncertainty the model utilizes Monte Carlo simulations for each subsystem and each component in subsystems (the simulation-based method). The model divides the plant into several subsystems based on the following considerations.

First is the loop-based consideration, i.e., four primary loops, one secondary loop, and the safety systems. The second consideration is based on possible power reduction when a subsystem fails, i.e., each primary loop contributes one fourth to the total power, a failure of the secondary loop will cause shutdown of the plant, and failure of safety systems will not cause any simultaneous power reduction (however, a decision about reducing power or even plant shutdown may be made afterward). Third, some thoughts were done regarding some particular components which are physically located in primary contour but those failures would cause one hundred percent of power reduction (reactor vessel and pressurizer).

Based on all the above the system was divided into six subsystems as following

- Subsystem #1: SG#1, PCP#1
- Subsystem #2: SG#2, PCP#2
- Subsystem #3: SG#3, PCP#3
- Subsystem #4: SG#4, PCP#4
- Subsystem #5: RV, PRES, TUR, CON, FWP
- Subsystem #6: CR, ECS

And the corresponding simultaneous coefficients for power reductions are

- Subsystem #1- Subsystem #4: ¼
- Subsystem #5: 1
- Subsystem #6: 0

Flow chart for the part of the code that corresponds to simulation-based corrective maintenance is shown on Figure 33. It can be seen from the figure that the simulations are done on a daily basis.

To follow the states of each subsystem at any particular day, the array "RTTR" (Remaining-Time-To-Repair) was introduced. If subsystem is operable (available) the corresponding element of the array is zero. Otherwise, the element reflects the number of days needed to repair that subsystem.

Every operating day is started in the code by checking if the subsystems are operable at this day (array "RTTR"). Then for all subsystems that are operable at the beginning of this day the code determines whether or not the subsystems fail during this day. To do that a random number between 0 and 1 is generated and system is said to be failed if this random number is less than the subsystem failure probability that is calculated based on following considerations.

Failure probability during time T (in simulation time T is equal to 1 day) can be expressed in terms of failure rate (FR) as

$$FP = FR \cdot T \tag{52}$$

where again $FR = \dfrac{1}{MTBF}$

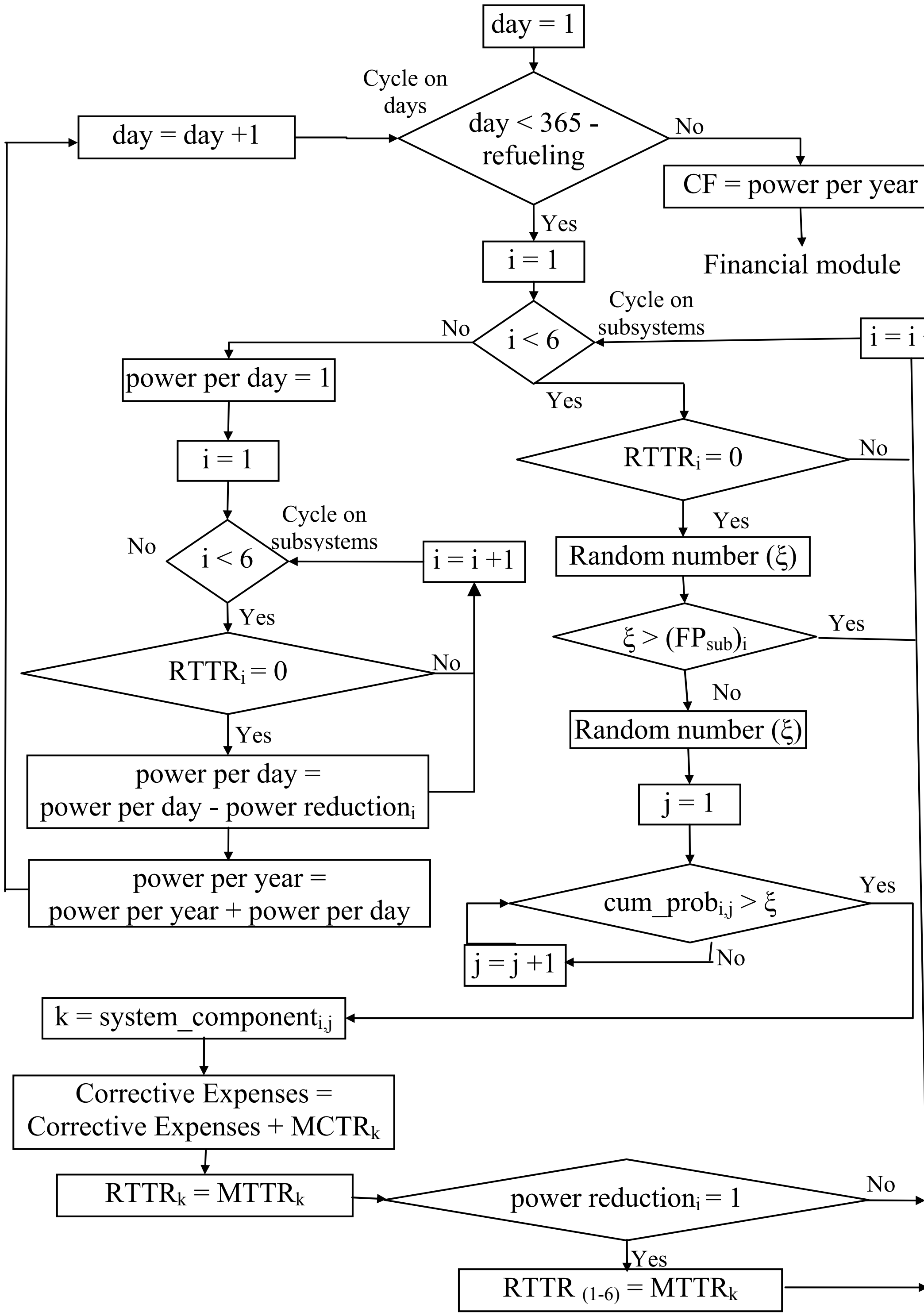


Figure 33. Flow chart for corrective maintenance

System MTBF can be calculated using definition of system unavailability (*U*) as fraction of time that system is unavailable to perform its design functions,

$$U = \frac{MTTR}{MTBF + MTTR} \tag{53}$$

then

$$MTBF = MTTR \cdot \left(\frac{1}{U} - 1 \right) \tag{54}$$

where MTTR for system is calculated as mean MTTR for the system components weighted by corresponding unavailabilities, i.e.,

$$MTTR = \frac{\sum_i MTTR_i \cdot U_i}{\sum_i U_i} \tag{55}$$

To determine which particular component in the failed subsystem causes the trouble, the matrix of cumulated probabilities (“cum_prob”) was created. Each column in the matrix represents one of the subsystems. The elements of the columns are filled out as following: the first element is the ratio of unavailability of the first component in the corresponding subsystem to sum of all components unavailabilities in that subsystem; the second element has the same denominator but the numerator in the ratio is sum of unavailability for first two components in the subsystem, and so on. The very last element in each column is one. At the next step, the second random number is generated; the place of this random number in the cumulative probability matrix determines the number of failed component.

When such component is found the code shuts the corresponding subsystem down for the time required to fix the failed component (corresponding element in the “RTTR” array is changed to the failed components’ mean-time-to-repair). If the failed component is a critical component (i.e., causes power reduction of one hundred percent) then the code shuts the whole system down for the time needed to repair the component. The cost to repair this component is added to the corrective maintenance expenses for this year.

After each day of simulation the code calculates the system power reduction occurring this day (if any) by determining which subsystem is unavailable this day and what power reduction it causes; as a consequence power produced on this particular day is calculated. At the end of the year these daily powers contribute into the system power per that year (actual capacity factor for the system).

SAFE-M Input/Output Structure

This section describes the structure of the second part of the model, the input/output file. This file utilizes Microsoft Excel with the Precision Tree 1.0 for Excel software (from Palisade Decision Tools Suits). As mentioned above, this file is used by the code for both input and output.

The input part of the file has the menu consisting of a number of buttons to simplify the process of browsing it. The menu is shown in Figure 34.

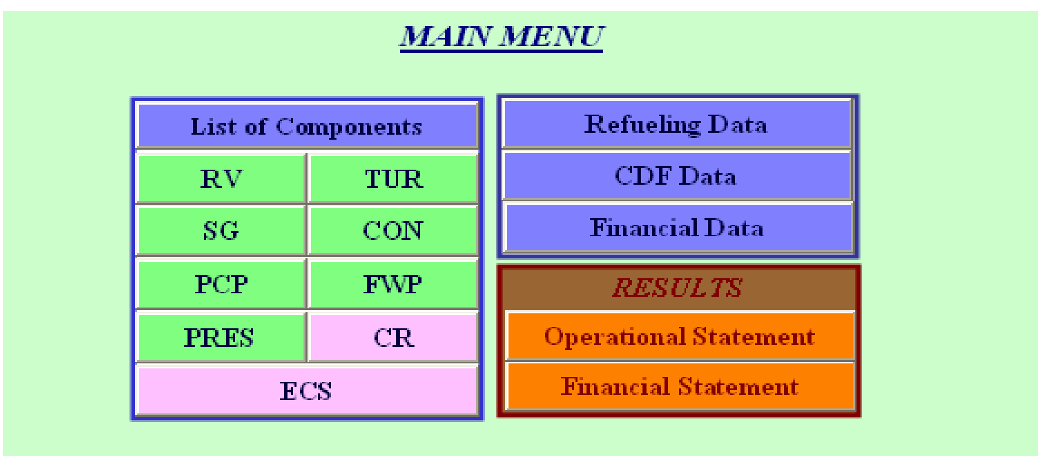


Figure 34. Main menu of the SAFE'M input/output file

Pressing any button will transfer a user to the corresponding spreadsheet. In order to return to the main menu the user will need to press the main menu button added into each spreadsheet that is accessible from the main menu. Let us go through each of the input buttons first and look at the structure of the corresponding spreadsheets.

The very first button is named as "List of Components". Pressing this one will transfer a user to another Excel spreadsheet as shown in Figure 35. The table shown there consists of three columns: component (i.e., component's name), abbreviation used in the model to make a reference to this component, and number of such components in the system. It needs to be mentioned here (and this is be common for all spreadsheets with input data) that every field with yellow (shaded) background is needed to be filled out before the model can be run. In other words, all input cells are in yellow background.

Component	Abrevia-tion	Number of Components
Reactor Vessel	RV	1
Steam Generator	SG	4
Primary Coolant Pump	PCP	4
Pressurizer	PRES	1
Turbine	TUR	1
Condencer	CON	1
Feed Water Pump	FWP	1
Control Rods	CR	1
Emergency Cooling System	ECS	1

Figure 35. Input data: list of system's components

The data shown in Figure 35 are common components of four-loop pressurized water reactors. The data can be changed by a user at any time if needed. The case of a new component added into the system, and necessary changes other than typing its name into the table shown in Figure 35, will be described later in the text.

The next nine buttons in the main menu corresponds to system components entered in the table in Figure 35 (one button for each one component name). The way the components are shown in that figure assumes that all four steam generators are initially identical (have the same characteristics); the same is true for primary coolant pumps. If this is not the case, then they should be entered as separate components.

Pressing any one of those nine buttons will open a spreadsheet with structure shown in Figure 36. Again everything with yellow (shaded) background is the input information for the model.

MTBF, days:	

Preventive maintenance (is conducted on-line or during refueling outages)				
Component	Work		Cost, \$M	Benefit, % to FR_{new}
	1	Work 1		
	2	Work 2		

The bath-tub curve		
δ_1, %	T, yr	δ_2, %

Corrective Maintenance		
MTTR		days
MCTR		\$M

Figure 36. Input data for components

As can be seen from the figure there are four tables there. The first table consists of just one piece of information: Mean-Time-Between-Failures (*MTBF*) for a brand new component. This value is entered in days and then used by the model to calculate initial failure rate for this peace of equipment.

The second table is dedicated to possible preventive maintenance for this component. Preventive maintenance does not wait until the component fails; based on the components condition it performs some activities on the component to illuminate its failure in future. Most commonly such activity is done while the system is on-line or during the planned outages (say, refueling). The data in this table is organized in four columns: (1) component's name, (2) possible works that could be done preventively with this component (examples of such work could be replacement of the component, fixing or replacement of one part of the component, and so on), (3) cost of each possible preventive activity on this component, and (4) benefit from such activity. At every moment of time the component has some failure rate which is actually going to be different from the failure rate of this component when it was new. The difference is due to aging of the components. If the component is replaced by a new one this difference will go away (i.e., the benefit from the replacement will be 100% of the difference). If any other work is done with the component then the benefit might be somewhere between zero and 100%, not including the upper boundary.

Moving further along the tables in Figure 36 leads to the table dedicated to aging process of component. To simulate component aging the model utilizes the bath-tub approach like the one described in the prototype model section of this text earlier. Each component will need three parameters to describe its aging process over time: two aging rates (δ_1 and δ_2) describing increase in the component failure rate over time and the time border for these two rates.

The last table in Figure 36 includes two parameters; both of them describe corrective maintenance. These parameters are Mean-Time-To-Repair (*MTTR*) for the component when it brakes and Mean-Cost-To-Repair (*MCTR*). These parameters are used by the model, along with the component failure rates, to estimate expected corrective maintenance expenses for the system each year.

The refueling data for the model includes only two parameters: refueling cycle and duration of refueling outages as shown in Figure 37. The sense of these parameters is described in the prototype model section.

Refueling Cycle	**18**	**months**
Refueling Outages	**27**	**days**

Figure 37. Input data: refueling data

The next button in the main menu is “CDF” which stands for Core-Damage-Frequency. The cell shown in Figure 38 is for the regulatory prescribed limit of CDF for the system. This value is used by the model to check whether the system is within the prescribed limits or not (see the flow chart section for details of this matter).

CDF_{limit}	**2.45E-04**	**1/yr**

Figure 38. Input data: core damage frequency

Other important input data entered (it would be more accurate to say here created) on this spreadsheet are event trees that are used by the model to calculate the CDF value for the system (these trees have already been described earlier in the CDF module section). The trees are linked to the cells with system component failure rates that are generated by the model during its work.

The last input related button on the main menu is “Financial Data.” The corresponding spreadsheet includes detailed data about financial part of system operation (Figure 39). These data are used by the model to conduct the financial statement for the system over a required time period (usually a year). Usage of some of these data (as depreciation, loan, and fuel data) has been discussed earlier in the text in the financial module section. Other categories are more-or-less self explanatory.

This spreadsheet also includes funds for preventive maintenance entered on the yearly basis (Figure 40). The data might be different from year to year as well as the same. As the funds are being entered they will appear on the graph to the right of the funds column (this graph was created there just for the visualization purposes).

FINANCIAL DATA

Income Tax Rate	
Property Tax Rate	
Inflation Rate	
NPV rate	

Plant Capacity, KW	

Types of customers	**% electricity sold**	**Price, $/KWh**
Residential		
Commercial		
Industrial		
Street Light		

Number of Fuel Assemblies		
Cost per fuel assembly		
Fraction Replaced		

Production Expense without fuel & maintenance	**Coolant & Water**	
	Electric	
	Operation Super & Eng	
	Steam	
	Miscellaneous	

Hourly labor par	**Rate per hour**	
	Number of hourly employees	
	Number of hours employed weekly	
	Number of weeks employed annually	

Loan	**Amount**	
	Interest Rate	
	Loan term	

Wages & Salaries	**Number of employees**	
	Average Salary	
	Number of executives	
	Exec Rate	

Administrative and General Expenses per year	**Employees Benefits and Pansions**	
	General Advertising Exp	
	Injuries and Damage Exp	
	Insurance Expense	
	Maint of Offices	
	Miscel Gen Exp	
	Office Expense	
	Regulatory Commission Exp	
	Rents	

Depreci ation	**Initial Cost**	
	Residual Value	
	Useful Life, yr	

Figure 39. Input data: financial data

Funds for preventive maintenance

Year	Funds, $
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	
21	
22	
23	
24	
25	
26	
27	
28	
29	
30	
31	
32	
33	
34	
35	
36	
37	
38	
39	
40	

Figure 40. Input data: preventive maintenance expenses

The last option available from this spreadsheet is related to corrective maintenance modeling (Figure 41). As it was discussed in the corrective maintenance section earlier in the text the model takes care about that type of maintenance in either way: through Monte-Carlo simulation or by calculating expected corrective maintenance expenses.

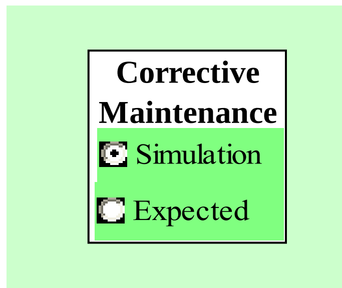


Figure 41. Input data: corrective maintenance choice

Now let us take a look at the output information structure. The file (the main menu) offers two output statements for any case run: operational and financial. The operational statement includes the following information:

- for each operational year a user will have the plant capacity factor, core damage frequency, and funds allocated into maintenance of the system; the information is presented in both table and graphical formats;
- at the end of the plant operation (40 years) a user will have list of all system components with their ages; that will allow the user to see when a component was replaced in the last time;
- detail table showing where the maintenance funds were allocated each year, i.e., a user will have list of components which were replaced or modified this year (indication what particular work has been done with the components).

The financial statement represents the so-called after taxes cash flow analysis and includes the following information in a table format (the information is on yearly basis)

- net sales;
- production expenses (without fuel and maintenance);
- fuel expenses;
- maintenance expenses;
- outside services expenses;
- administrative and general expenses (without wages and salaries);
- wages and salaries expenses;
- total expenses;
- depreciation amount;
- loan payments (interest payments and principal reduction payments);
- taxable income;
- taxes;
- after taxes cash flows;
- after taxes cash flow net present values;
- some of the data is also presented in a graphical format.

Examples of output will appear in "Results" section below.

Adding a New Component into the System

The system is designed to work with the components shown in Figure 35. If a user changes parameters of those components only, not the list itself, the model will handle such changes automatically and new set of results will be produced. If the user is introducing a new component (or components) into the system then some additional actions are required from the user before the model is able to handle the new components. Those actions are following.

1. The new component (component's name, suitable abbreviation for the component, and number of such components in the system) must be added into

the table shown in Figure 35 (pressing button "List of Components" on the main menu will open the spreadsheet with that table).

2. The new spreadsheet must be created and called by the new component abbreviation.
3. On that spreadsheet initial data (parameters) for the new component must be entered. It is very important that the data was entered in the same way (the same cells) as is done with any other system components. That is why it might be easier to just copy the data from another component spreadsheet and then modify this data for the new component.
4. On the spreadsheet called "CDF" (pressing button "CDF" on the main menu will open this spreadsheet) the existing event trees must be modified (if needed) according to the new component, and again, if needed, new separate event trees for the new component must be created. The following must be added in the code: output of the new component's failure rate into this spreadsheet, and this failure rate (more accurate to say is the cell containing the failure rate) must be linked to the new/modified event trees. Results from the sequences ended on core meltdown must be linked to the cell calculating the system core damage frequency on the same spreadsheet.
5. Go to the description of capacity factor calculation in the text (the capacity factor module) and see how the introducing this new component into the system will change the equation for the system capacity factor. The same changes must be done in the code (the Capacity_Factor subroutine).

Results

The goal of testing of the model was to get logically expected behavior of the system (as for the case of the prototype model). A hypothetical system (in terms of initial data) was created for this purpose. Appendix A includes parameters (input data) for the hypothetical system. Several characteristic cases conducted on this system are discussed below. Appendix B shows additional results received for this system that are not included in this section.

Case 1. Aging

The very first case was a demonstration of the system aging process. No preventive actions (preventive maintenance expenses equaled zero dollars per year) were taken during the system operation to slow down the aging process (pure aging). Only the corrective maintenance activities were performed on the system when needed (when any component of the system failed). Figure 42 shows the results for this case in terms of behavior of the system capacity factor, funds allocated into the system maintenance and core damage frequency over the operating years. Over the years as the system aged it started to fail more often and as a consequence of that the system capacity factor went down. On the other hand more system failed more corrective maintenance actions it required and thus, funds spent for corrective maintenance of the system increased over time. And of course since the system started to fail often its reliability went down and as a consequence the system core damage frequency went up over time. To demonstrate this case the model safety constraint was turned off; otherwise the model would not allow to go so far with the core damage frequency, the simulation would be stopped by the model as soon as the value of core damage frequency reached the maximum allowable by the model, at that moment the corresponding warning message would be given to a user. This simulation was based on the expected value of corrective maintenance. Oscillations in capacity factor from year to year are due to refueling outages every 18 months. Additional results for this case are shown in Appendix B (case 1).

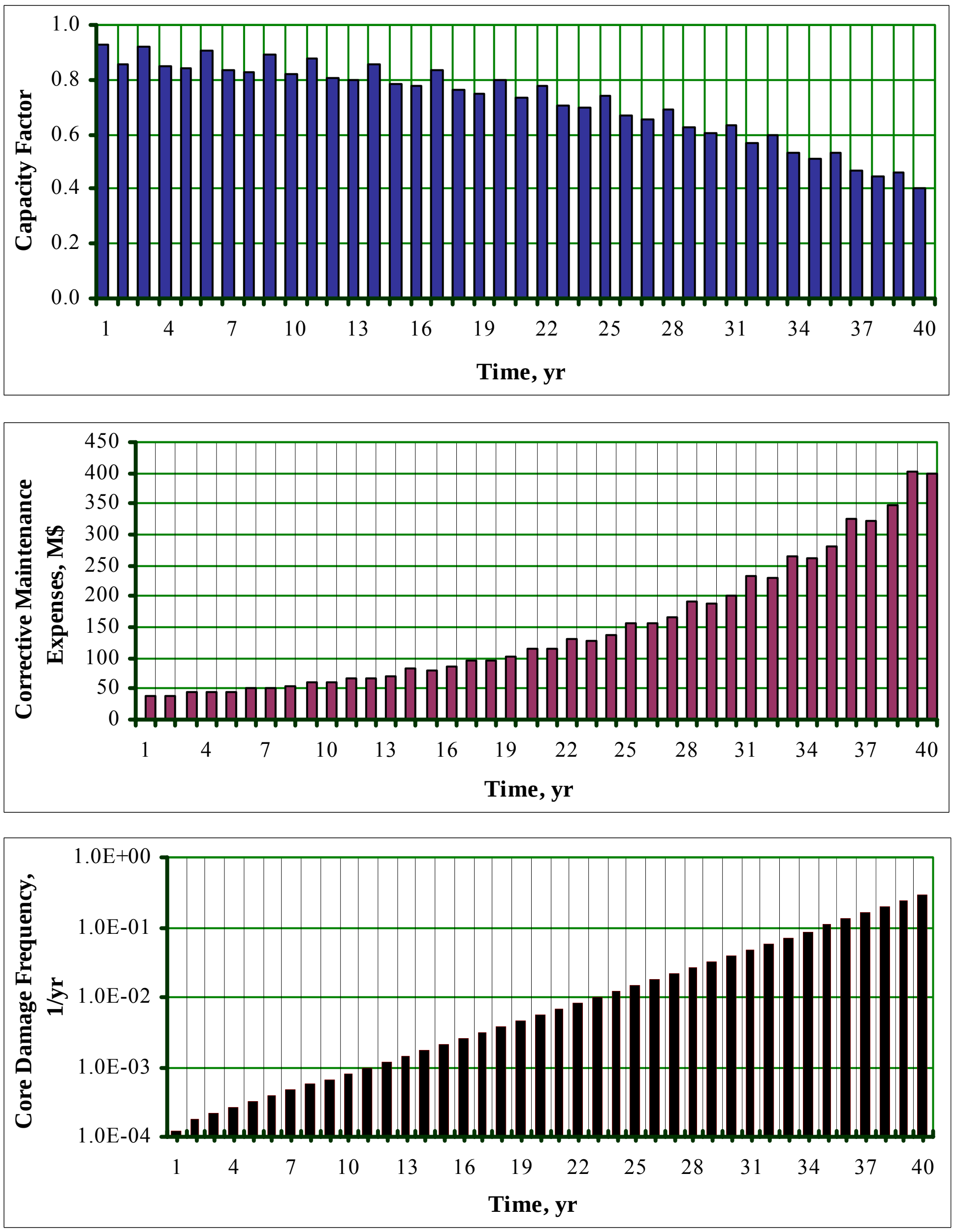


Figure 42. Demonstration of pure aging process for the hypothetical system

Case 2. Preventive vs. Corrective Maintenance

The next case was about the relationship between preventive and corrective maintenance spending. Logically the more you pay attention to your system (doing more activities to prevent system failure) the fewer failures you have and therefore the less expensive your corrective maintenance is. To demonstrate this effect the model was run with two different preventive maintenance budget (constant over years), 10M$/yr and 25M$/yr. The results are shown in Figure 43.

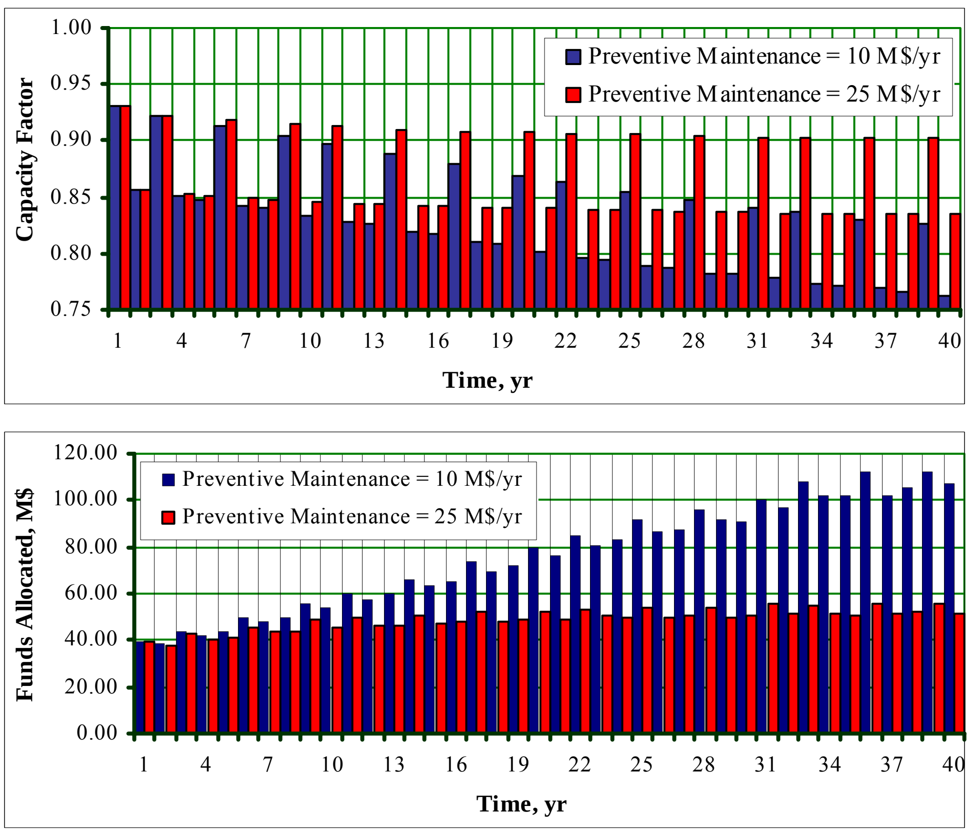


Figure 43. Preventive vs. corrective maintenance

The first graph on the figure shows the system capacity factor over time. It can be seen that while the system is still new there is almost no difference between these two cases; but with time when the aging process become dominant and the system starts to fail more often the difference became more visible. And it might require some time (mean-time-to-repair) to return the system in the fully operable condition. Thus a failure may increase system time out of service that in its turn will decrease the system capacity factor. Oscillations in capacity factor are again due to refueling outages every 18 months. The second graph on the figure shows expected corrective maintenance expenses for each operating year. Additional results for this case are shown in Appendix B (case 2).

Case 3. Preventive Maintenance Expenses Are Just Enough to Keep the System within the Safety Constraints

Two cases were conducted here: to keep CDF within 100% from the CDF value of the brand new system and within 50%. First the preventive maintenance expenses were set up at the zero level for each operational year. Then if the safety constraints were violated the expenses were increased until the system safety performance indicator was back to the prescribed limits. The results are shown in Figure 44.

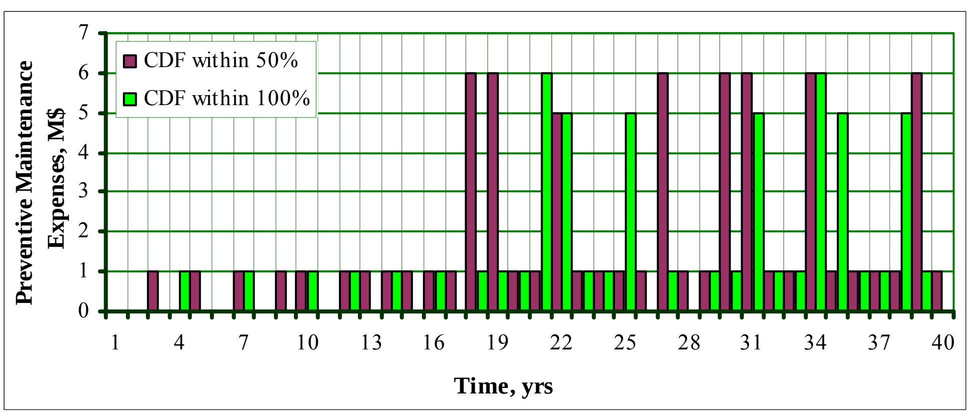


Figure 44. Preventive maintenance expenses to keep CDF within the limits

It can be seen from the figure that more strict limitations on CDF led to bigger preventive maintenance efforts is required, and the effort starts earlier in the system operation. Oscillations start when the cumulated degradation of equipment (due to natural aging) drives value of CDF out of prescribed bounds; in order to return it back more effort in terms of preventive maintenance expenses is required. Additional results for this case are shown in Appendix B (case 3 and case 4).

Case 4. Preventive Maintenance Expenses Are Just Enough to Maintain System Capacity Factor at a Constant Level (No Safety Constraints)

These cases also show that in order to keep the system at higher performance one needs to allocate more money to it. In these cases the system was asked to keep its capacity factor at a level of 80% and then at a level of 85% per year. The results are shown in Figure 45.

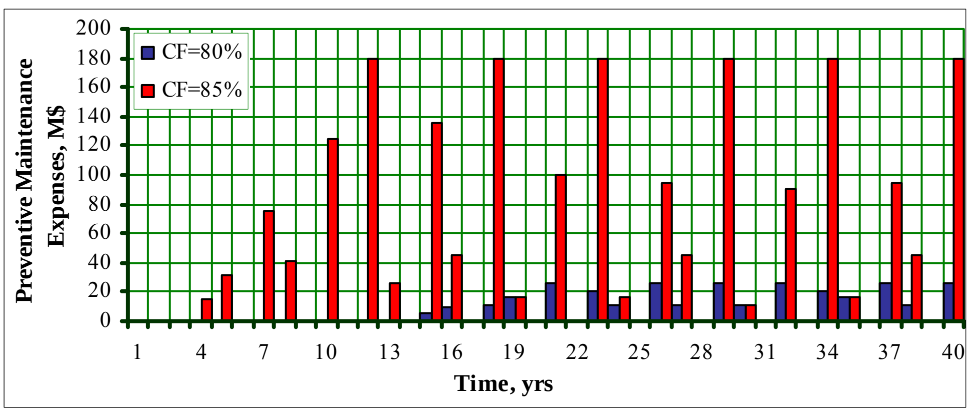


Figure 45. Preventive maintenance expenses to keep constant capacity factor (no safety constraints)

The results showed that to maintain higher capacity factor requires bigger preventive maintenance effort; but in these particular cases benefit of about 30 million dollars (in terms of accumulated profit NPV) was gained from maintaining the system capacity factor at level of 85% per year compared to 80% per year (see additional results for this case in Appendix B (cases 5-7)).

Case 5. Optimum Preventive Maintenance Expenses (Constant over Time)

The goal for the next case was to find the optimum preventive maintenance expenses, considering them to be constant for each year over the system operating time. The results of this case are shown in Figure 46. As one can see from the figure for this hypothetical system that was tested preventive maintenance expenses in amount of 25M$ per year are optimum in terms of accumulated profit net present value (net present values for profit for each operating year are sum up at the end of operation (assumed 40 years operating period)). Again, as in the case of the previous tests, the model safety constraints were turned off, otherwise the model would not allow to have such spending for the system preventive maintenance as zero per year (the very left point on the graph).

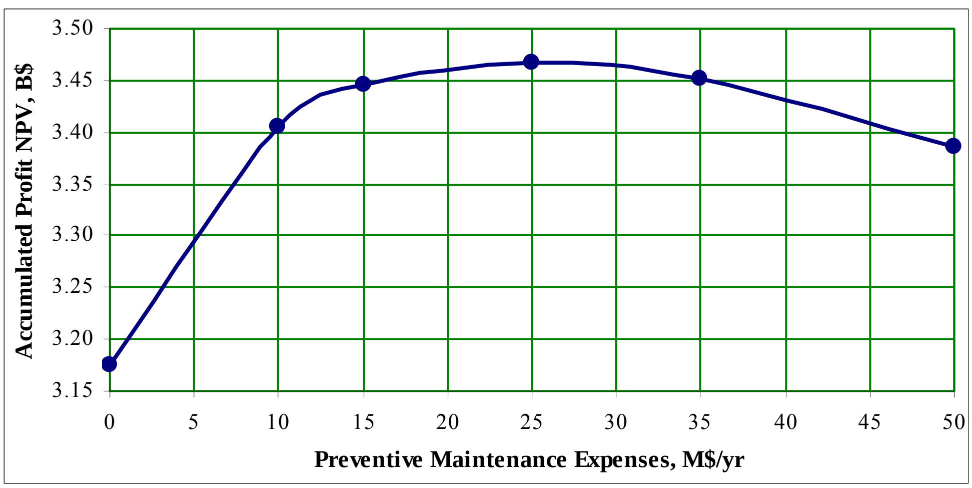


Figure 46. Optimum preventive maintenance expenses

Case 6. Optimum Preventive Maintenance Expenses on Yearly Basis

If the previous case assumed that each year will have the same amount of preventive maintenance expenses, then this case actually started from the previous case results and run the optimization on the yearly basis i.e., the model found the optimum amount of the preventive maintenance expenses for each particular year (one at a time starting from year 1). Again accumulated profit net present value was used as a criterion for the optimization (maximization). This case was conducted with the safety constraint turned on (the core damage frequency was allowed to fluctuate within 100 percent from that value of the brand-new system). The results are shown in Figure 47.

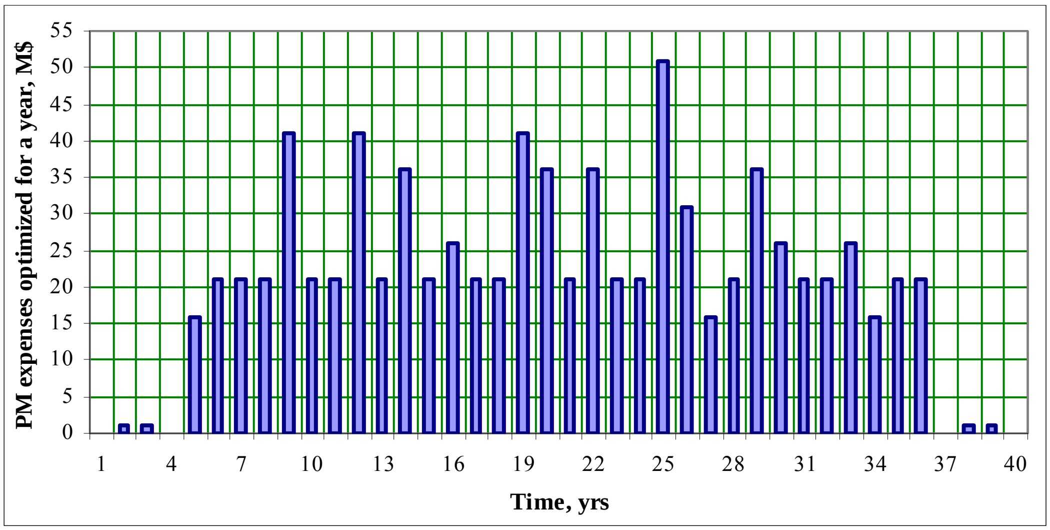


Figure 47. Optimum preventive maintenance expenses for a year

The benefit from preventive maintenance activities usually lasts for several years after the activity was done (until the natural effect of wearing out do not eat the benefit up). When the system is new there is no reason for any preventive maintenance (if you preventively replace a new component by the same new one the benefit from such replacement will be close to zero). That is why the first several years on the figure required either nothing or very little preventive maintenance. Over the time when the system components failure rates increase (due to natural aging effect) the system starts to require some activities to be done to prevent the aged component from the failure. At this time some major upgrades preventively performed on the system may be in order (picks on the graph). This is the reason of increased preventive maintenance expenses during the middle time of operation. As it was mentioned above the effect from the preventive maintenance lasts for several years after the maintenance was performed. At the very end of operation there is no particular reasons of doing any major system upgrade because the benefit from those would be seen after the system has already complete its operation (the very right part of the graph). The benefit from this optimization in terms of accumulated profit NPV is $17.4 M comparing to case 4 above. Note that the approach of this example can be construed as applying a heuristic "greedy" algorithm (Kuo et al., 2001) to the problem of maximizing net present value of cumulative profit over a supposed plant life. Hence it is not assured to produce an absolute optimum; however, it is the logical approach using SAFE-M, and the comparison to the results of case 4 demonstrates a significant benefit.

Case 7. Simulation

As was mentioned above the model can run on the so-called expected basis (using failure rates, mean-time-to-repair, and mean-cost-to-repair) as well as on the simulations base (using the Monte-Carlo method). All the results described above were obtained by using the expected method. This case in its turn was conducted to show the simulation capabilities of the model. For this particular case two simulations were done (with 1 run of the model per year, and 1000 runs of the model per each year with the following averaging results for these 1000 runs); the system safety constraints were within 100 % from the CDF value for the brand new one . The results are shown in Figure 48.

It can be seen from the figure that the error in prediction of the system capacity factor is within 0.35% (i.e., the prediction is quite accurate).

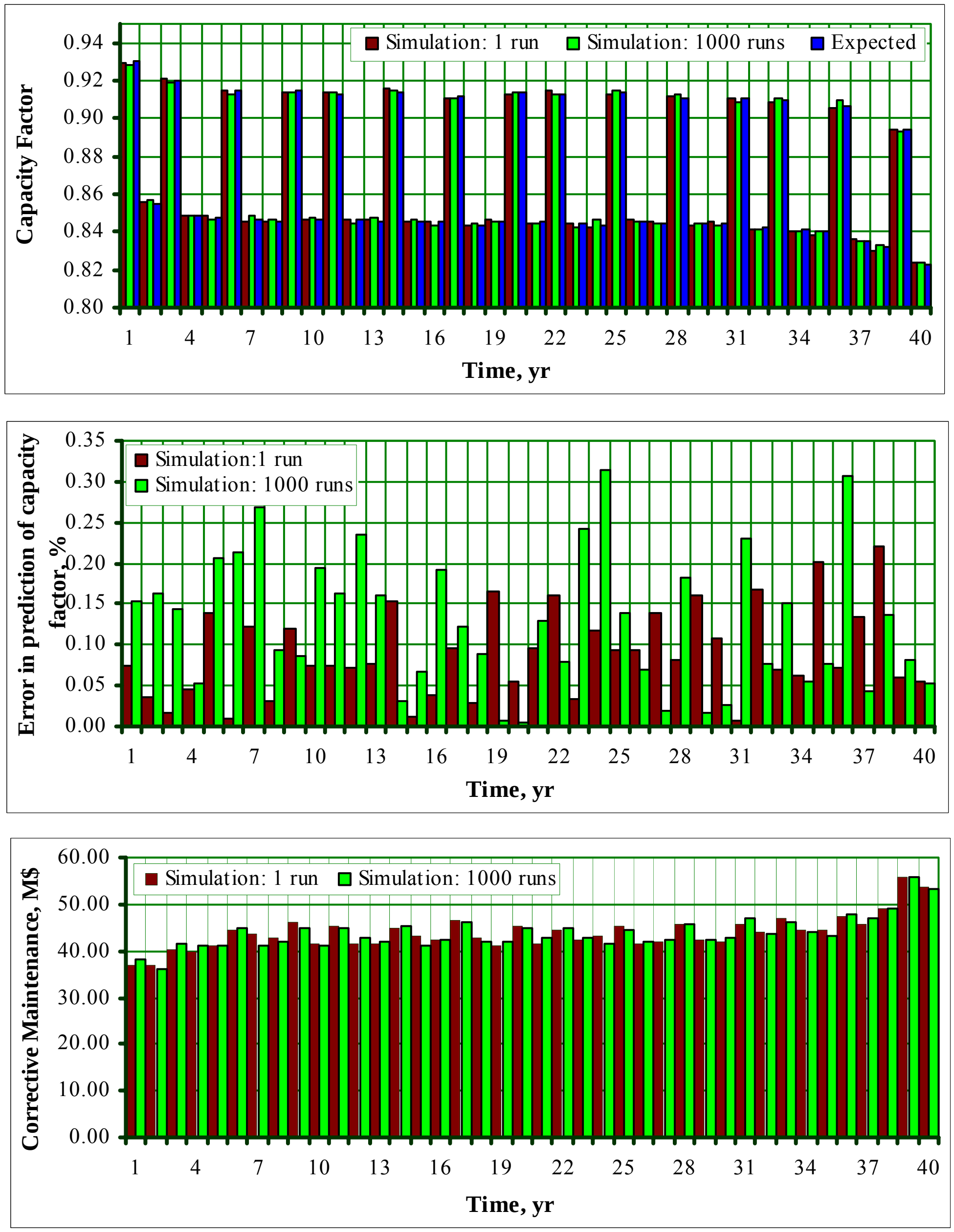


Figure 48. Simulation results

CONCLUSIONS

A computerized model of a PWR-design reactor system was developed. The model allows to see how maintenance allocation into the system can influence not only the system operational and as a consequence economics (i.e., financial) performances, but also the system safety constrains.

The model utilizes the following features:

- preventive maintenance (through capacity factor optimization under the CDF limits);
- corrective maintenance (calculation can be performed on the expected basis or through Monte Carlo daily simulation);
- capacity factor calculation (based on the system components availability);
- system core damage frequency calculation (using PRA methodology).

Numerous cases were run to test the model. The results showed that the model can be used as a simulation tool to model a real plant operation. Both operational and financial statements are produced by the model for each year of the system operation. Even though the present version of the model includes only major big components of a real system, the model has a build in capability for expansion (new components can be introduced into the system by a user when needed).

The following software is used by the model:

- Visual Basic.Net (for writing the code of the model);
- Microsoft Excel (for input/output of the model); and
- Precision Tree 1.0 for Excel by Palisade Inc. (for constructing event trees and CDF calculations).

The next thing to do by way of further development of the model would be performing of uncertainties analysis. For now the model uses point estimates for equipment failure rates and cost data (it assumes that those data age known with 100% certainty). In the real life those data would be distributions. Also depending on user's needs the model could be expanded (adding more components) to get more detailed analysis of the system.

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APPENDIX A

INPUT DATA FOR THE HYPOTHETICAL SYSTEM

Component	Abrevia-tion	Number of Components
Reactor Vessel	RV	1
Steam Generator	SG	4
Primary Coolant Pump	PCP	4
Pressurizer	PRES	1
Turbine	TUR	1
Condenser	CON	1
Feed Water Pump	FWP	1
Control Rods	CR	1
Emergency Cooling System	ECS	1

Figure A.1. List of components

Refueling Cycle	18	months
Refueling Outages	27	days

Figure A.2. Refueling data

MTBF, days:	7.00E+03

Preventive maintenance (is conducted on-line or during refueling outages)			
	Work	Cost, $M	Benefit, % to FR_{new}
Reactot Vessel	1 Replacement	20	100
	2 Work 2	7	22

The bath-tub curve		
δ_1, %	T, yr	δ_2, %
1.2	40	1.2

Corrective Maintenance		
MTTR	26	days
MCTR	5	$M

Figure A.3. Input data for reactor vessel

MTBF, days:	500

Preventive maintenance (is conducted on-line or during refueling outages)			
Steam Generators	Work	Cost, \$M	Benefit, % to FR_{new}
	1 Replacement	125	100
	2 Work 2	5	20

The bath-tub curve		
δ_1, %	T, yr	δ_2, %
5	20	10

Corrective Maintenance		
MTTR	20	days
MCTR	10	\$M

Figure A.4. Input data for steam generators

MTBF, days:	2000

Preventive maintenance (is conducted on-line or during refueling outages)			
Primary Coolant Pumps	Work	Cost, \$M	Benefit, % to FR_{new}
	1 Replacement	10	100
	2 Work 2	5	80

The bath-tub curve		
δ_1, %	T, yr	δ_2, %
10	20	15

Corrective Maintenance		
MTTR	15	days
MCTR	5	\$M

Figure A.5. Input data for primary coolant pumps

MTBF, days:	1800

Preventive maintenance (is conducted on-line or during refueling outages)			
Pressurizer	Work	Cost, \$M	Benefit, % to FR_{new}
	1 Replacement	30	100
	2 Work 2	10	60

The bath-tub curve		
δ_1, %	T, yr	δ_2, %
4	20	8

Corrective Maintenance		
MTTR	10	days
MCTR	5	\$M

Figure A.6. Input data for pressurizer

MTBF, days:	**1.00E+04**

Preventive maintenance (is conducted on-line or during refueling outages)			
Component	**Work**	**Cost, \$M**	**Benefit, % to FR_{new}**
Turbine	1 Replacement	**50**	**100**
	2 Work 2	**10**	**50**

The bath-tub curve		
δ_1, %	T, yr	δ_2, %
5	**20**	**10**

Corrective Maintenance		
MTTR	**10**	**days**
MCTR	**10**	**\$M**

Figure A.7. Input data for turbine

MTBF, days:	**1500**

Preventive maintenance (is conducted on-line or during refueling outages)			
Condenser	**Work**	**Cost, \$M**	**Benefit, % to FR_{new}**
	1 Replacement	**20**	**100**
	2 Work 2	**5**	**50**

The bath-tub curve		
δ_1, %	T, yr	δ_2, %
2	**20**	**5**

Corrective Maintenance		
MTTR	**15**	**days**
MCTR	**9**	**\$M**

Figure A.8. Input data for condenser

MTBF, days:	**1750**

Preventive maintenance (is conducted on-line or during refueling outages)			
Feed Water Pumps	**Work**	**Cost, \$M**	**Benefit, % to FR_{new}**
	1 Replacement	**5**	**100**
	2 Work 2	**1**	**70**

The bath-tub curve		
δ_1, %	T, yr	δ_2, %
10	**20**	**15**

Corrective Maintenance		
MTTR	**10**	**days**
MCTR	**5**	**\$M**

Figure A.9. Input data for feed water pump

MTBF, days:	1.00E+07

Preventive maintenance (is conducted on-line or during refueling outages)			
Component	**Work**	**Cost, $M**	**Benefit, % to FR_{new}**
Control Rods	1 Replacement	6	100
	2 Work 2	3	70

The bath-tub curve		
δ_1, %	T, yr	δ_2, %
1.5	20	3

Corrective Maintenance		
MTTR	30	days
MCTR	5	$M

Figure A.10. Input data for control rods

MTBF, days:	1.00E+05

Preventive maintenance (is conducted on-line or during refueling outages)			
Emergency Cooling System	**Work**	**Cost, $M**	**Benefit, % to FR_{new}**
	1 Replacement	50	100
	2 Work 2	10	70

The bath-tub curve		
δ_1, %	T, yr	δ_2, %
2	20	4

Corrective Maintenance		
MTTR	20	days
MCTR	15	$M

Figure A.11. Input data for emergency cooling system

FINANCIAL DATA

Income Tax Rate	35%
Property Tax Rate	1%
Inflation Rate	3%
NPV rate	8%

Plant Capacity, KW	1000000

Types of customers	% electricity sold	Price, $/KWh
Residential	30.5%	0.145
Commercial	36.5%	0.119
Industrial	28.0%	0.096
Street Light	5.0%	0.272

Number of Fuel Assemblies	250
Cost per fuel assembly	$400,000
Fraction Replaced	33%

Production Expense without fuel & maintenance	Coolant & Water	$2,235,000
	Electric	$832,000
	Operation Super & Eng	$22,720,000
	Steam	$22,160,000
	Miscellaneous	$31,230,000

Hourly labor par	Rate per hour	25
	Number of hourly employees	75
	Number of hours employed weekly	20
	Number of weeks employed annually	52

Loan	Amount	$2,000,000,000
	Interest Rate	10.0%
	Loan term	30

Wages & Salaries	Number of employees	100
	Average Salary	$50,000
	Number of executives	15
	Exec Rate	$100,000

Administrative and General Expenses per year	Employees Benefits and Pansions	$15,000,000
	General Advertising Exp	$50,000
	Injuries and Damage Exp	$1,500,000
	Insurance Expense	$342,000
	Maint of Offices	$40,000
	Miscel Gen Exp	$150,000
	Office Expense	$886,000
	Regulatory Commission Exp	$6,000
	Rents	$700,000

Depreci ation	Initial Cost	$2,000,000,000
	Residual Value	$100,000,000
	Useful Life, yr	39

Figure A.12. Financial input data

APPENDIX B

ADDITIONAL RESULTS FOR THE HYPOTHETICAL SYSTEM

Case 1. Aging

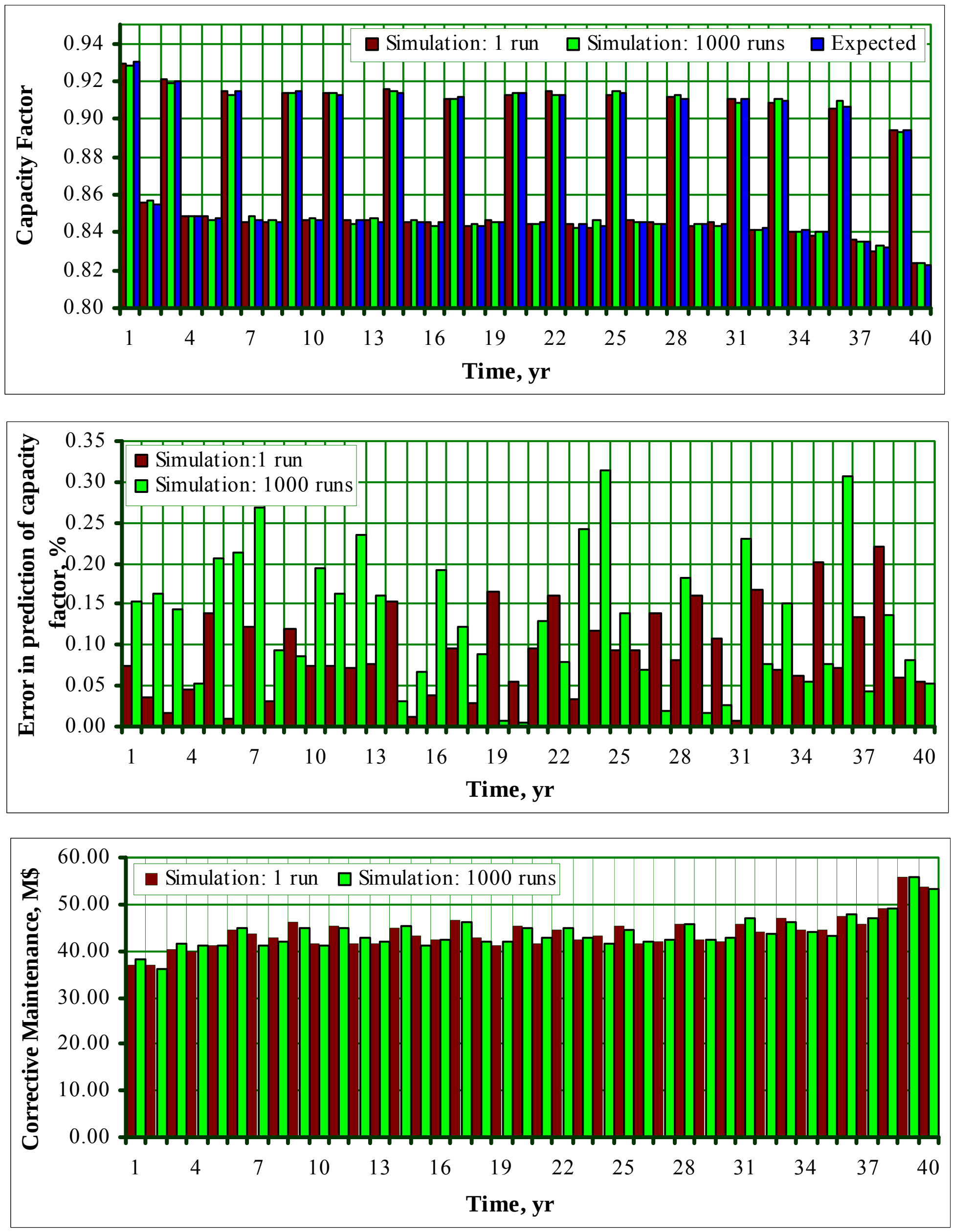


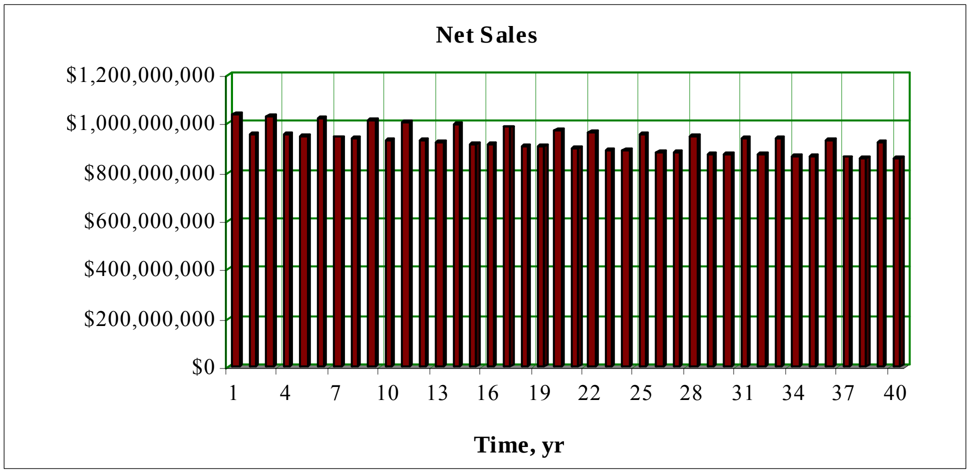
Figure B.1. Financial graphs for the pure aging case

End of Year	Net Sales	Expenses							Depreciation Amount	Loan		Taxable Income	Taxes	ATCF	ATCF NPV
		Production (w/o fuel & maintenance)	Fuel	Preventive Maintenance	Outside Services	Administrative & General (w/o wages & salaries)	Wages & Salaries	Total		Interest	Principal Reduction				
1	$1,043,912,712	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$27,820,000	$200,000,000	$4,981,968	$669,978,202	$234,492,371	$458,323,863	$412,013,541
2	$959,246,647	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$199,501,803	$5,480,165	$529,960,287	$185,486,100	$390,276,073	$315,391,486
3	$1,031,489,681	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$198,953,787	$6,028,181	$630,688,429	$220,740,950	$455,201,349	$330,689,648
4	$950,884,763	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$198,350,969	$6,630,999	$518,374,893	$181,431,213	$381,594,732	$249,205,975
5	$946,321,815	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$197,687,869	$7,294,099	$512,082,906	$179,229,017	$376,841,841	$221,235,194
6	$1,016,688,979	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$196,958,459	$8,023,509	$610,122,755	$213,542,964	$439,838,333	$232,127,821
7	$936,346,803	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$196,156,108	$8,825,860	$498,396,220	$174,438,677	$366,413,734	$173,838,066
8	$930,897,535	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$195,273,522	$9,708,446	$490,956,173	$171,834,660	$360,695,117	$153,834,031
9	$999,013,408	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$194,302,677	$10,679,291	$585,780,915	$205,023,320	$421,360,355	$161,549,214
10	$918,974,167	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$193,234,748	$11,747,220	$474,759,573	$166,165,851	$348,128,554	$119,985,798
11	$985,344,647	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$192,060,026	$12,921,942	$567,096,733	$198,483,857	$406,972,986	$126,094,110
12	$905,536,018	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$190,767,832	$14,214,136	$456,627,864	$159,819,752	$333,876,026	$92,993,688
13	$898,188,990	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$189,346,418	$15,635,550	$446,763,831	$156,367,341	$326,042,991	$81,636,077
14	$961,514,904	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$187,782,863	$17,199,105	$534,765,243	$187,167,835	$381,680,354	$85,910,468
15	$882,109,532	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$186,062,953	$18,919,015	$425,282,685	$148,848,940	$308,796,781	$62,482,452
16	$873,322,250	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$184,171,051	$20,810,917	$413,599,091	$144,759,682	$299,310,544	$54,443,537
17	$933,016,198	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$182,089,959	$22,892,009	$496,422,052	$173,747,718	$351,064,376	$57,405,050
18	$854,109,046	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$179,800,759	$25,181,209	$388,171,284	$135,859,949	$278,412,176	$40,925,178
19	$843,623,800	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$177,282,638	$27,699,330	$374,354,504	$131,024,076	$266,913,148	$35,270,478
20	$899,015,178	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$174,512,705	$30,469,263	$451,015,137	$157,855,298	$313,972,627	$37,296,853
21	$820,745,628	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$171,465,778	$33,516,190	$344,329,498	$120,515,324	$241,580,035	$25,797,668
22	$872,860,776	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$168,114,159	$36,867,809	$416,264,709	$145,692,648	$284,986,304	$27,357,879
23	$795,126,008	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$164,427,378	$40,554,590	$310,867,352	$108,803,573	$212,791,240	$18,363,320
24	$781,217,282	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$160,371,919	$44,610,049	$292,756,254	$102,464,689	$196,963,568	$15,279,966
25	$827,773,979	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$155,910,915	$49,071,053	$356,579,526	$124,802,834	$233,987,689	$16,318,059
26	$751,075,515	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$151,003,809	$53,978,159	$253,604,083	$88,761,429	$162,146,547	$10,165,347
27	$734,800,263	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$145,605,993	$59,375,975	$232,502,341	$81,375,819	$143,032,598	$8,060,993
28	$775,031,522	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$139,668,396	$65,313,572	$286,892,902	$100,412,516	$172,448,866	$8,736,810
29	$699,765,910	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$133,137,039	$71,844,929	$187,123,469	$65,493,214	$101,067,377	$4,603,017
30	$680,992,719	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$125,952,546	$79,029,422	$162,811,497	$56,984,024	$78,080,102	$3,196,767
31	$714,216,386	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$118,049,604	$86,932,364	$206,395,274	$72,238,346	$98,506,615	$3,625,559
32	$640,950,791	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$109,356,367	$95,625,601	$110,904,043	$38,816,415	$27,744,078	$917,950
33	$669,217,393	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$99,793,807	$105,188,161	$146,528,178	$51,284,862	$41,337,206	$1,229,501
34	$597,702,995	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$89,274,991	$115,706,977	$54,662,024	$19,131,708	-$28,894,610	-$772,580
35	$574,960,384	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$77,704,293	$127,277,675	$24,968,154	$8,738,854	-$59,766,323	-$1,436,555
36	$595,596,966	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$64,976,526	$140,005,442	$47,592,715	$16,657,450	-$57,788,127	-$1,248,657
37	$527,504,790	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$50,975,982	$154,005,987	-$37,363,833	-$13,077,342	-$127,010,427	-$2,467,079
38	$502,935,657	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$35,575,383	$169,406,585	-$69,885,652	-$24,459,978	-$163,550,208	-$2,855,840
39	$516,099,757	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$18,634,724	$186,347,244	-$61,385,819	-$21,485,037	-$174,965,975	-$2,746,473
40	$452,568,344	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$23,540,000	$0	$0	-$109,517,431	-$38,331,101	-$47,646,330	-$672,342

Accumulated Profit NPV:	**$3,175,781,975**

Figure B.2. Financial statement for the pure aging case

Case 2. Preventive Maintenance vs. Corrective Maintenance



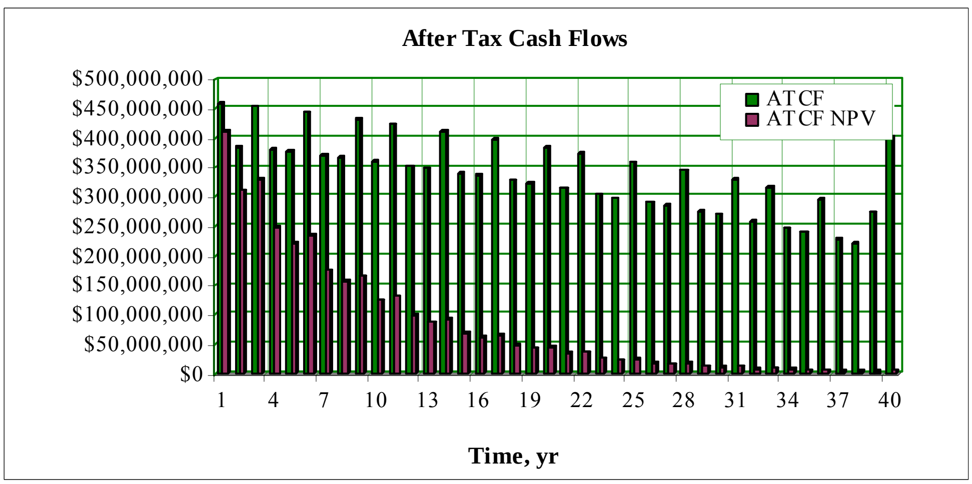


Figure B.3. Preventive maintenance expenses are 10M$/yr

End of Year	Net Sales	Expenses							Depreciation Amount	Loan		Taxable Income	Taxes	ATCF	ATCF NPV
		Production (w/o fuel & maintenance)	Fuel	Maintenance	Outside Services	Administrative & General (w/o wages & salaries)	Wages & Salaries	Total		Interest	Principal Reduction				
1	$1,043,912,712	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$27,820,000	$200,000,000	$4,981,968	$669,978,202	$234,492,371	$458,323,863	$412,013,541
2	$960,691,380	$79,177,000	$33,333,333	$10,000,000	$1,950,000	$18,674,000	$6,500,000	$149,634,333	$51,282,051	$199,501,803	$5,480,165	$521,749,780	$182,612,423	$384,939,243	$311,078,666
3	$1,034,117,374	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$198,953,787	$6,028,181	$628,040,282	$219,814,099	$453,480,053	$329,439,180
4	$954,710,188	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$198,350,969	$6,630,999	$517,341,610	$181,069,563	$380,923,098	$248,767,354
5	$951,913,042	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$197,687,869	$7,294,099	$513,439,528	$179,703,835	$377,723,645	$221,752,881
6	$1,024,692,548	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$196,958,459	$8,023,509	$614,714,728	$215,150,155	$442,823,115	$233,703,062
7	$945,796,541	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$196,156,108	$8,825,860	$504,962,337	$176,736,818	$370,681,710	$175,862,927
8	$942,637,749	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$195,273,522	$9,708,446	$500,870,688	$175,304,741	$367,139,552	$156,582,540
9	$1,014,562,403	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$194,302,677	$10,679,291	$600,917,290	$210,321,052	$431,198,999	$165,321,342
10	$936,329,680	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$193,234,748	$11,747,220	$492,419,189	$172,346,716	$359,607,304	$123,942,058
11	$1,007,699,708	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$192,060,026	$12,921,942	$592,047,866	$207,216,753	$423,191,222	$131,119,073
12	$929,951,790	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$190,767,832	$14,214,136	$484,891,363	$169,711,977	$352,247,301	$98,110,596
13	$926,759,633	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$189,346,418	$15,635,550	$480,904,226	$168,316,479	$348,234,248	$87,192,421
14	$997,353,228	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$187,782,863	$17,199,105	$579,723,925	$202,903,374	$410,903,498	$92,488,155
15	$920,411,960	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$186,062,953	$18,919,015	$473,799,321	$165,829,763	$340,332,595	$68,863,460
16	$917,063,940	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$184,171,051	$20,810,917	$470,450,188	$164,657,566	$336,263,757	$61,165,197
17	$986,724,374	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$182,089,959	$22,892,009	$567,668,130	$198,683,845	$397,374,327	$64,977,522
18	$910,358,190	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$179,800,759	$25,181,209	$463,795,503	$162,328,426	$327,567,919	$48,150,823
19	$907,114,254	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$177,282,638	$27,699,330	$460,601,751	$161,210,613	$322,973,859	$42,678,461
20	$976,021,049	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$174,512,705	$30,469,263	$557,869,953	$195,254,484	$383,428,257	$45,547,497
21	$900,469,554	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$171,465,778	$33,516,190	$456,140,792	$159,649,277	$314,257,376	$33,558,682
22	$968,635,216	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$168,114,159	$36,867,809	$552,020,413	$193,207,145	$373,227,511	$35,828,785
23	$893,473,882	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$164,427,378	$40,554,590	$451,551,990	$158,043,196	$304,236,255	$26,254,782
24	$892,005,480	$79,177,000	$33,333,333	$10,000,000	$1,950,000	$18,674,000	$6,500,000	$149,634,333	$51,282,051	$160,371,919	$44,610,049	$447,809,420	$156,733,297	$297,748,126	$23,098,592
25	$959,919,486	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$155,910,915	$49,071,053	$548,902,219	$192,115,776	$358,997,440	$25,036,110
26	$885,508,784	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$151,003,809	$53,978,159	$450,947,567	$157,831,649	$290,419,811	$18,207,099
27	$884,483,664	$79,177,000	$33,333,333	$10,000,000	$1,950,000	$18,674,000	$6,500,000	$149,634,333	$51,282,051	$145,605,993	$59,375,975	$450,905,337	$157,816,868	$284,994,546	$16,061,647
28	$951,689,887	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$139,668,396	$65,313,572	$552,379,685	$193,332,890	$345,015,275	$17,479,575
29	$877,831,398	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$133,137,039	$71,844,929	$455,878,447	$159,557,456	$275,758,113	$12,559,139
30	$876,947,267	$79,177,000	$33,333,333	$10,000,000	$1,950,000	$18,674,000	$6,500,000	$149,634,333	$51,282,051	$125,952,546	$79,029,422	$458,865,636	$160,602,972	$270,515,292	$11,075,476
31	$943,531,753	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$118,049,604	$86,932,364	$561,448,346	$196,506,921	$329,291,112	$12,119,637
32	$873,271,260	$79,177,000	$33,333,333	$10,000,000	$1,950,000	$18,674,000	$6,500,000	$149,634,333	$51,282,051	$109,356,367	$95,625,601	$466,406,198	$163,242,169	$258,820,479	$8,563,421
33	$939,845,573	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$99,793,807	$105,188,161	$568,894,002	$199,112,901	$315,874,992	$9,395,132
34	$866,892,989	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$89,274,991	$115,706,977	$479,107,505	$167,687,627	$246,994,952	$6,604,117
35	$866,466,374	$79,177,000	$33,333,333	$10,000,000	$1,950,000	$18,674,000	$6,500,000	$149,634,333	$51,282,051	$77,704,293	$127,277,675	$486,075,484	$170,126,419	$239,953,441	$5,767,567
36	$932,355,469	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$64,976,526	$140,005,442	$591,934,839	$207,177,194	$296,034,255	$6,396,563
37	$862,962,648	$79,177,000	$33,333,333	$10,000,000	$1,950,000	$18,674,000	$6,500,000	$149,634,333	$51,282,051	$50,975,982	$154,005,987	$508,666,886	$178,033,410	$227,909,541	$4,426,967
38	$859,917,877	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$35,575,383	$169,406,585	$521,883,942	$182,659,380	$221,100,028	$3,860,749
39	$928,114,551	$79,177,000	$0	$10,000,000	$1,950,000	$18,674,000	$6,500,000	$116,301,000	$51,282,051	$18,634,724	$186,347,244	$629,221,077	$220,227,377	$273,928,507	$4,299,906
40	$856,484,079	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$23,540,000	$0	$0	$579,819,115	$202,936,690	$400,422,425	$5,650,400

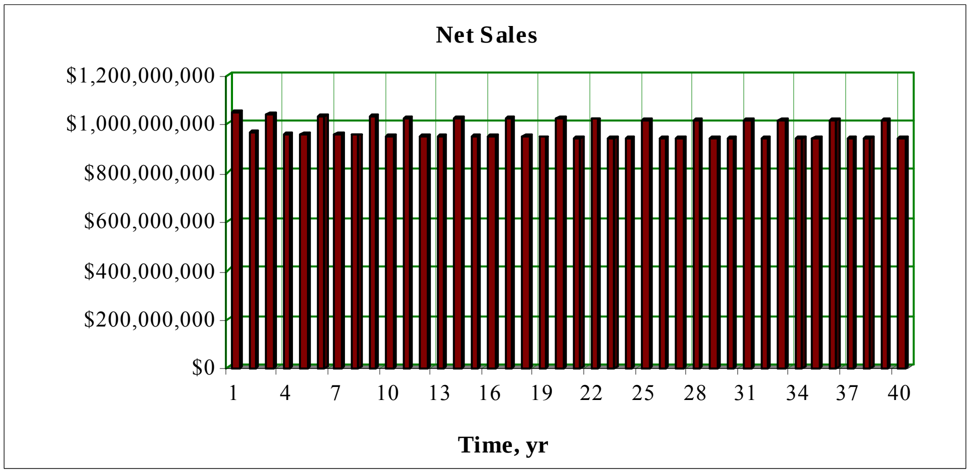
Accumulated Net Profit NPV:	$3,405,001,102

Figure B.4. Financial statement for the case with preventive maintenance expenses of 10M$/yr

Components	Operating Years																																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Reactor Vessel																																								
Steam Generator #1														W							W						W				W						W			
Steam Generator #2								W								W							W					W						W			W			
Steam Generator #3												W								W						W				W						W			W	
Steam Generator #4											W							W							W					W					W				W	
Primary Coolant Pump #1		W				W							W		W							W											W							
Primary Coolant Pump #2			W				W																	W											W					
Primary Coolant Pump #3				W					W								W										W											W		
Primary Coolant Pump #4					W					W									W										W											W
Pressurizer																																W								
Turbine																																								
Condencer																								W																
Feed Water Pump		R	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W		W	W		W	W		W		W	W		W		W		W
Control Rods																																								
Emergency Cooling System																																								

R - replacement, W - work 2

Figure B.5. Work table for the case with preventive maintenance expenses of 10M$/yr



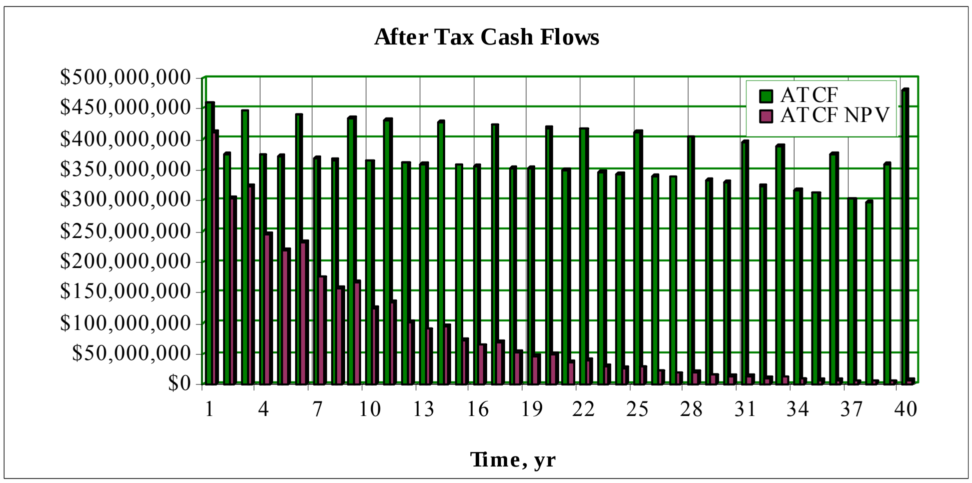


Figure B.6. Preventive maintenance expenses are 25M$/yr

End of Year	Net Sales	Expenses							Depreciation Amount	Loan		Taxable Income	Taxes	ATCF	ATCF NPV
		Production (w/o fuel & maintenance)	Fuel	Maintenance	Outside Services	Administrative & General (w/o wages & salaries)	Wages & Salaries	Total		Interest	Principal Reduction				
1	$1,043,912,712	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$27,820,000	$200,000,000	$4,981,968	$669,978,202	$234,492,371	$458,323,863	$412,013,541
2	$961,591,912	$79,177,000	$33,333,333	$25,000,000	$1,950,000	$18,674,000	$6,500,000	$164,634,333	$51,282,051	$199,501,803	$5,480,165	$508,076,192	$177,826,667	$376,051,411	$303,896,195
3	$1,035,923,415	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$198,953,787	$6,028,181	$615,868,004	$215,553,801	$445,568,072	$323,691,372
4	$957,322,706	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$198,350,969	$6,630,999	$506,464,486	$177,262,570	$373,852,968	$244,150,103
5	$955,689,772	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$197,687,869	$7,294,099	$504,652,922	$176,628,523	$372,012,351	$218,399,911
6	$1,030,245,746	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$196,958,459	$8,023,509	$609,200,416	$213,220,146	$439,238,812	$231,811,420
7	$952,614,943	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$196,156,108	$8,825,860	$501,155,660	$175,404,481	$368,207,370	$174,689,023
8	$951,367,389	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$195,273,522	$9,708,446	$500,229,247	$175,080,236	$366,722,615	$156,404,719
9	$1,026,206,980	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$194,302,677	$10,679,291	$604,773,986	$211,670,895	$433,705,851	$166,282,467
10	$949,171,687	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$193,234,748	$11,747,220	$498,775,372	$174,571,380	$363,738,823	$125,366,025
11	$1,024,145,108	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$192,060,026	$12,921,942	$603,920,576	$211,372,202	$430,908,484	$133,510,143
12	$947,717,016	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$190,767,832	$14,214,136	$498,528,797	$174,485,079	$361,111,633	$100,579,557
13	$946,952,437	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$189,346,418	$15,635,550	$499,172,190	$174,710,266	$360,108,425	$90,165,530
14	$1,021,541,188	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$187,782,863	$17,199,105	$604,788,850	$211,676,098	$427,195,699	$96,155,283
15	$945,354,738	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$186,062,953	$18,919,015	$500,150,236	$175,052,583	$357,460,690	$72,329,187
16	$944,776,690	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$184,171,051	$20,810,917	$500,412,914	$175,144,520	$355,739,529	$64,707,771
17	$1,019,872,498	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$182,089,959	$22,892,009	$606,866,943	$212,403,430	$422,853,556	$69,143,813
18	$943,839,634	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$179,800,759	$25,181,209	$503,809,660	$176,333,381	$353,577,121	$51,974,044
19	$943,275,957	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$177,282,638	$27,699,330	$505,216,979	$176,825,943	$351,973,757	$46,510,570
20	$1,018,241,222	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$174,512,705	$30,469,263	$612,466,774	$214,363,371	$418,916,191	$49,763,113
21	$942,448,115	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$171,465,778	$33,516,190	$510,057,461	$178,520,111	$349,303,211	$37,301,130
22	$1,017,053,797	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$168,114,159	$36,867,809	$617,601,094	$216,160,383	$415,854,954	$39,920,899
23	$941,284,558	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$164,427,378	$40,554,590	$514,766,260	$180,168,191	$345,325,530	$29,800,678
24	$941,127,864	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$160,371,919	$44,610,049	$518,850,337	$181,597,618	$343,924,722	$26,680,863
25	$1,016,140,502	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$155,910,915	$49,071,053	$627,872,261	$219,755,291	$410,327,967	$28,615,848
26	$940,620,560	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$151,003,809	$53,978,159	$527,741,154	$184,709,404	$340,335,643	$21,336,440
27	$940,077,146	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$145,605,993	$59,375,975	$532,332,936	$186,316,527	$337,922,485	$19,044,546
28	$1,014,799,577	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$139,668,396	$65,313,572	$642,436,596	$224,852,809	$403,552,267	$20,445,246
29	$939,336,048	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$133,137,039	$71,844,929	$544,260,481	$190,491,168	$333,206,434	$15,175,568
30	$938,955,986	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$125,952,546	$79,029,422	$550,306,723	$192,607,353	$329,951,999	$13,508,943
31	$1,013,556,467	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$118,049,604	$86,932,364	$661,624,391	$231,568,537	$394,405,541	$14,516,189
32	$938,367,057	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$109,356,367	$95,625,601	$566,072,325	$198,125,314	$323,603,461	$10,706,852
33	$1,013,065,884	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$99,793,807	$105,188,161	$679,496,972	$237,823,940	$387,766,922	$11,533,428
34	$937,908,320	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$89,274,991	$115,706,977	$585,303,786	$204,856,325	$316,022,535	$8,449,767
35	$937,639,245	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$77,704,293	$127,277,675	$597,058,398	$208,970,439	$312,092,335	$7,501,512
36	$1,012,327,508	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$64,976,526	$140,005,442	$713,076,396	$249,576,739	$374,776,267	$8,097,982
37	$937,230,733	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$50,975,982	$154,005,987	$622,999,518	$218,049,831	$302,225,751	$5,870,501
38	$937,323,098	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$35,575,383	$169,406,585	$637,635,087	$223,172,280	$296,338,273	$5,174,525
39	$1,012,167,942	$79,177,000	$0	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$127,301,000	$51,282,051	$18,634,724	$186,347,244	$759,252,520	$265,738,382	$358,448,945	$5,626,639
40	$936,958,990	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$23,540,000	$0	$0	$701,351,841	$245,473,144	$479,418,697	$6,765,124

Accumulated Net Profit NPV:	**$3,467,616,467**

Figure B.7. Financial statement for the case with preventive maintenance expenses of 25M$/yr

Components	Operating Years																																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Reactor Vessel																																								
Steam Generator #1			W		W	W		W		W	W		W	W		W		W	W		W	W		W	W		W	W		W		W	W		W		W		W	W
Steam Generator #2			W		W	W			W	W		W	W	W			W	W		W	W	W			W	W		W	W		W	W		W	W		W		W	W
Steam Generator #3			W		W	W		W		W		W	W	W			W	W		W	W	W		W		W	W		W	W		W		W	W		W		W	W
Steam Generator #4				W		W		W	W	W			W	W	W		W	W		W		W		W	W	W		W	W		W		W		W	W		W	W	
Primary Coolant Pump #1		W		W			W				W				W				W				W				W					W				W				
Primary Coolant Pump #2		W		W			W				W				W				W				W				W				W					W				W
Primary Coolant Pump #3		W			W			W				W				W				W					W				W				W				W	W		
Primary Coolant Pump #4		W		W			W				W				W				W					W				W					W							
Pressurizer									W							W							W							W								W		
Turbine																																		W						
Condencer			W				W					W					W				W					W					W					W				
Feed Water Pump		R	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
Control Rods																																								
Emergency Cooling System																																								

R - replacement, W - work 2

Figure B.8. Work table for the case with preventive maintenance expenses of 25M$/yr

Case 3. Preventive Maintenance is just enough to keep core damage frequency within 100% change compared with the brand new system

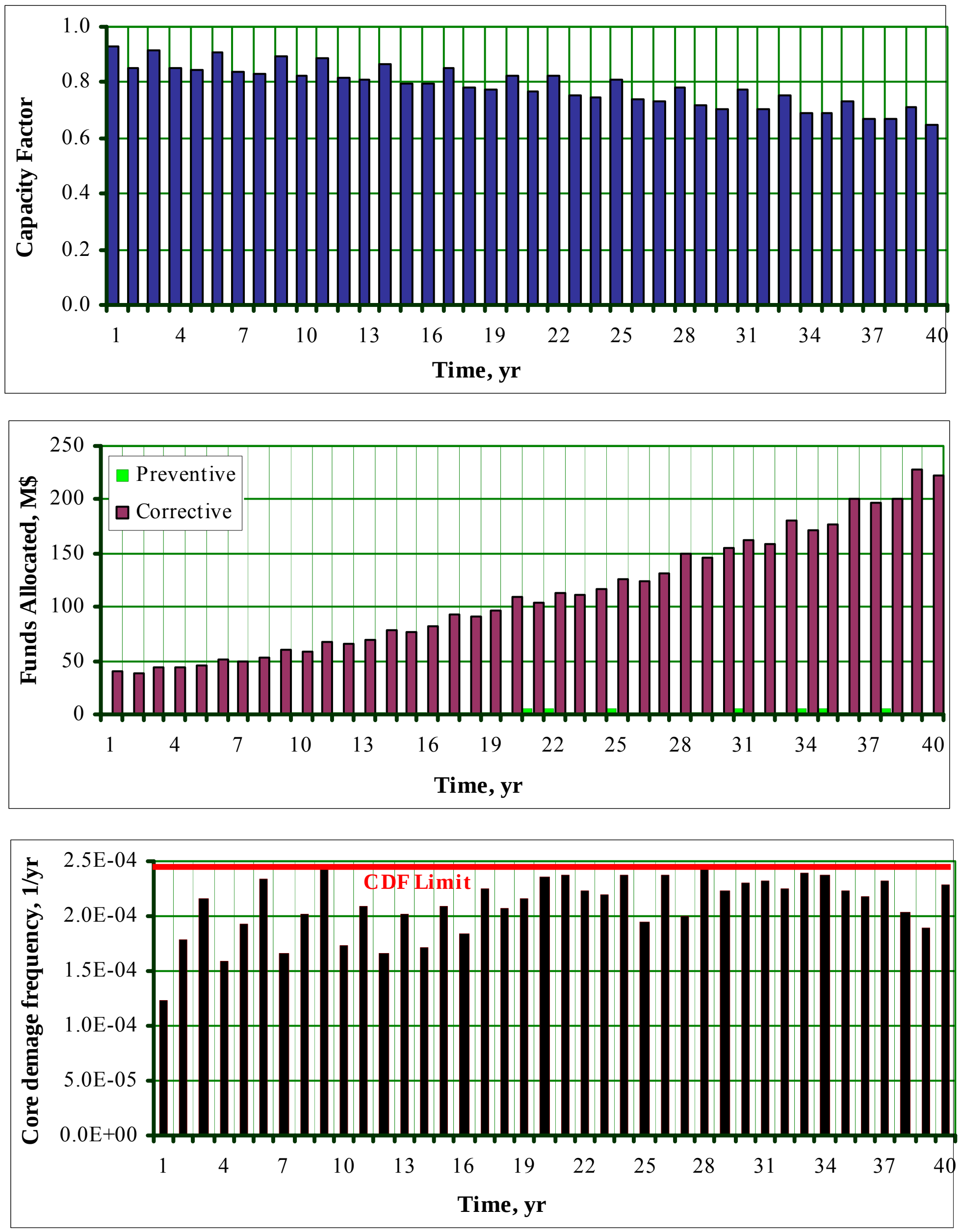
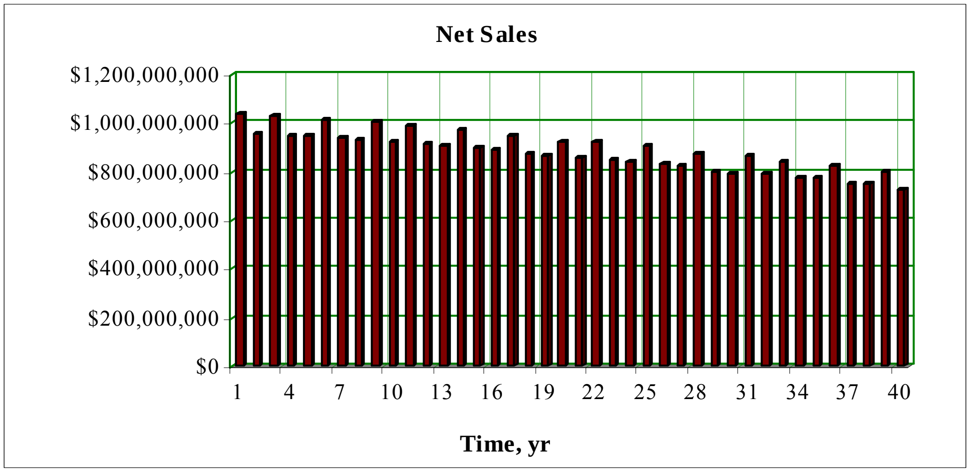


Figure B.9. CDF is kept within 100% limit



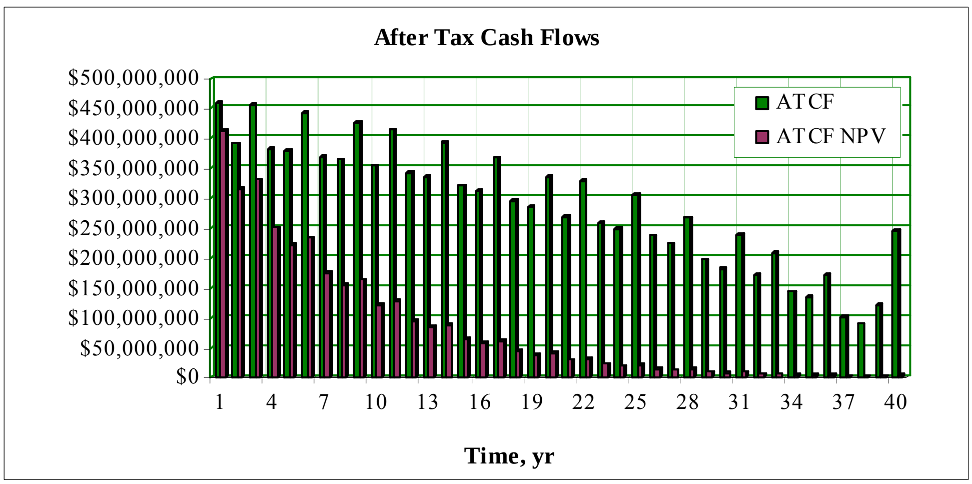


Figure B.10. Financial graphs for the case when CDF is kept within 100% limit

End of Year	Net Sales	Expenses							Depreciation Amount	Loan		Taxable Income	Taxes	ATCF	ATCF NPV
		Production (w/o fuel & maintenance)	Fuel	Maintenance	Outside Services	Administrative & General (w/o wages & salaries)	Wages & Salaries	Total		Interest	Principal Reduction				
1	$1,043,912,712	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$27,820,000	$200,000,000	$4,981,968	$669,978,202	$234,492,371	$458,323,863	$412,013,541
2	$959,246,647	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$199,501,803	$5,480,165	$529,960,287	$185,486,100	$390,276,073	$315,391,486
3	$1,031,489,681	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$198,953,787	$6,028,181	$630,688,429	$220,740,950	$455,201,349	$330,689,648
4	$952,638,568	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$198,350,969	$6,630,999	$519,442,430	$181,804,851	$382,288,631	$249,659,136
5	$948,240,503	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$197,687,869	$7,294,099	$514,346,698	$180,021,344	$378,313,306	$222,099,057
6	$1,018,954,862	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$196,958,459	$8,023,509	$612,798,578	$214,479,502	$441,577,618	$233,045,741
7	$940,566,347	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$196,156,108	$8,825,860	$502,382,369	$175,833,829	$369,004,731	$175,067,316
8	$935,508,997	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$195,273,522	$9,708,446	$496,410,901	$173,743,815	$364,240,691	$155,346,195
9	$1,004,453,270	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$194,302,677	$10,679,291	$592,222,468	$207,277,864	$425,547,364	$163,154,510
10	$926,447,529	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$193,234,748	$11,747,220	$482,616,411	$168,915,744	$353,235,498	$121,745,955
11	$994,153,257	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$192,060,026	$12,921,942	$577,548,732	$202,142,056	$413,766,785	$128,199,061
12	$915,906,154	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$190,767,832	$14,214,136	$467,945,778	$163,781,022	$341,232,671	$95,042,717
13	$909,496,388	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$189,346,418	$15,635,550	$460,213,785	$161,074,825	$334,785,462	$83,825,055
14	$976,204,004	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$187,782,863	$17,199,105	$551,260,039	$192,941,014	$392,401,972	$88,323,742
15	$896,923,841	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$186,062,953	$18,919,015	$442,954,962	$155,034,237	$320,283,762	$64,806,746
16	$890,645,161	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$184,171,051	$20,810,917	$433,295,333	$151,653,366	$312,113,101	$56,772,277
17	$953,361,144	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$182,089,959	$22,892,009	$520,774,076	$182,270,927	$366,893,192	$59,993,333
18	$875,740,344	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$179,800,759	$25,181,209	$413,109,605	$144,588,362	$294,622,085	$43,307,953
19	$867,835,358	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$177,282,638	$27,699,330	$402,445,734	$140,856,007	$285,172,448	$37,683,301
20	$928,003,688	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$174,512,705	$30,469,263	$484,923,648	$169,723,277	$336,013,159	$39,915,050
21	$858,392,739	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$171,465,778	$33,516,190	$386,438,833	$135,253,592	$268,951,103	$28,720,550
22	$926,444,003	$79,177,000	$0	$5,000,000	$1,950,000	$18,674,000	$6,500,000	$111,301,000	$51,282,051	$168,114,159	$36,867,809	$482,488,098	$168,870,834	$328,031,506	$31,490,097
23	$849,732,652	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$164,427,378	$40,554,590	$382,623,004	$133,918,051	$259,432,414	$22,388,330
24	$840,884,654	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$160,371,919	$44,610,049	$371,514,604	$130,030,111	$248,156,495	$19,251,391
25	$909,954,629	$79,177,000	$0	$5,000,000	$1,950,000	$18,674,000	$6,500,000	$111,301,000	$51,282,051	$155,910,915	$49,071,053	$464,804,977	$162,681,742	$304,334,233	$21,223,954
26	$833,172,226	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$151,003,809	$53,978,159	$367,323,965	$128,563,388	$236,064,470	$14,799,435
27	$824,565,128	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$145,605,993	$59,375,975	$356,327,188	$124,714,516	$223,518,749	$12,597,011
28	$879,304,373	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$139,668,396	$65,313,572	$432,812,448	$151,484,357	$267,296,571	$13,542,098
29	$804,604,048	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$133,137,039	$71,844,929	$333,625,787	$116,769,025	$196,293,884	$8,940,017
30	$794,081,260	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$125,952,546	$79,029,422	$321,977,964	$112,692,287	$181,538,305	$7,432,568
31	$865,674,445	$79,177,000	$0	$5,000,000	$1,950,000	$18,674,000	$6,500,000	$111,301,000	$51,282,051	$118,049,604	$86,932,364	$422,057,652	$147,720,178	$238,687,160	$8,784,937
32	$791,737,255	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$109,356,367	$95,625,601	$331,379,552	$115,982,843	$171,053,159	$5,659,522
33	$843,526,683	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$99,793,807	$105,188,161	$403,949,498	$141,382,324	$208,661,064	$6,206,247
34	$777,734,666	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$89,274,991	$115,706,977	$319,128,969	$111,695,139	$143,008,904	$3,823,752
35	$774,450,996	$79,177,000	$33,333,333	$5,000,000	$1,950,000	$18,674,000	$6,500,000	$144,634,333	$51,282,051	$77,704,293	$127,277,675	$323,928,004	$113,374,801	$134,557,579	$3,234,252
36	$824,979,775	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$64,976,526	$140,005,442	$400,268,265	$140,093,893	$171,450,982	$3,704,629
37	$752,826,492	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$50,975,982	$154,005,987	$313,693,968	$109,792,889	$101,177,144	$1,965,288
38	$750,518,423	$79,177,000	$33,333,333	$5,000,000	$1,950,000	$18,674,000	$6,500,000	$144,634,333	$51,282,051	$35,575,383	$169,406,585	$318,354,879	$111,424,208	$88,806,137	$1,550,693
39	$798,606,398	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$18,634,724	$186,347,244	$393,346,668	$137,671,334	$120,610,142	$1,893,240
40	$727,370,510	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$23,540,000	$0	$0	$341,737,804	$119,608,231	$245,669,573	$3,466,667

Accumulated Net Profit NPV:	**$3,296,756,496**

Figure B.11. Financial statement for the case when CDF is kept within 100% limit

Components	Operating Years																																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Reactor Vessel																																								
Steam Generator #1																																								
Steam Generator #2																																								
Steam Generator #3																																								
Steam Generator #4																																								
Primary Coolant Pump #1																					W													W						
Primary Coolant Pump #2																						W													W					
Primary Coolant Pump #3																									W													W		
Primary Coolant Pump #4																															W									
Pressurizer																																								
Turbine																																								
Condencer																																								
Feed Water Pump				W			W			W		W		W		W		W	W	W	W		W	W			W		W	W		W	W	W		W	W		W	
Control Rods																																								
Emergency Cooling System																																								

R - replacement, W - work 2

Figure B.12. Work table for the case when CDF is kept within 100% limit

Case 4. Preventive Maintenance is just enough to keep core damage frequency within 50% change compared with the brand new system

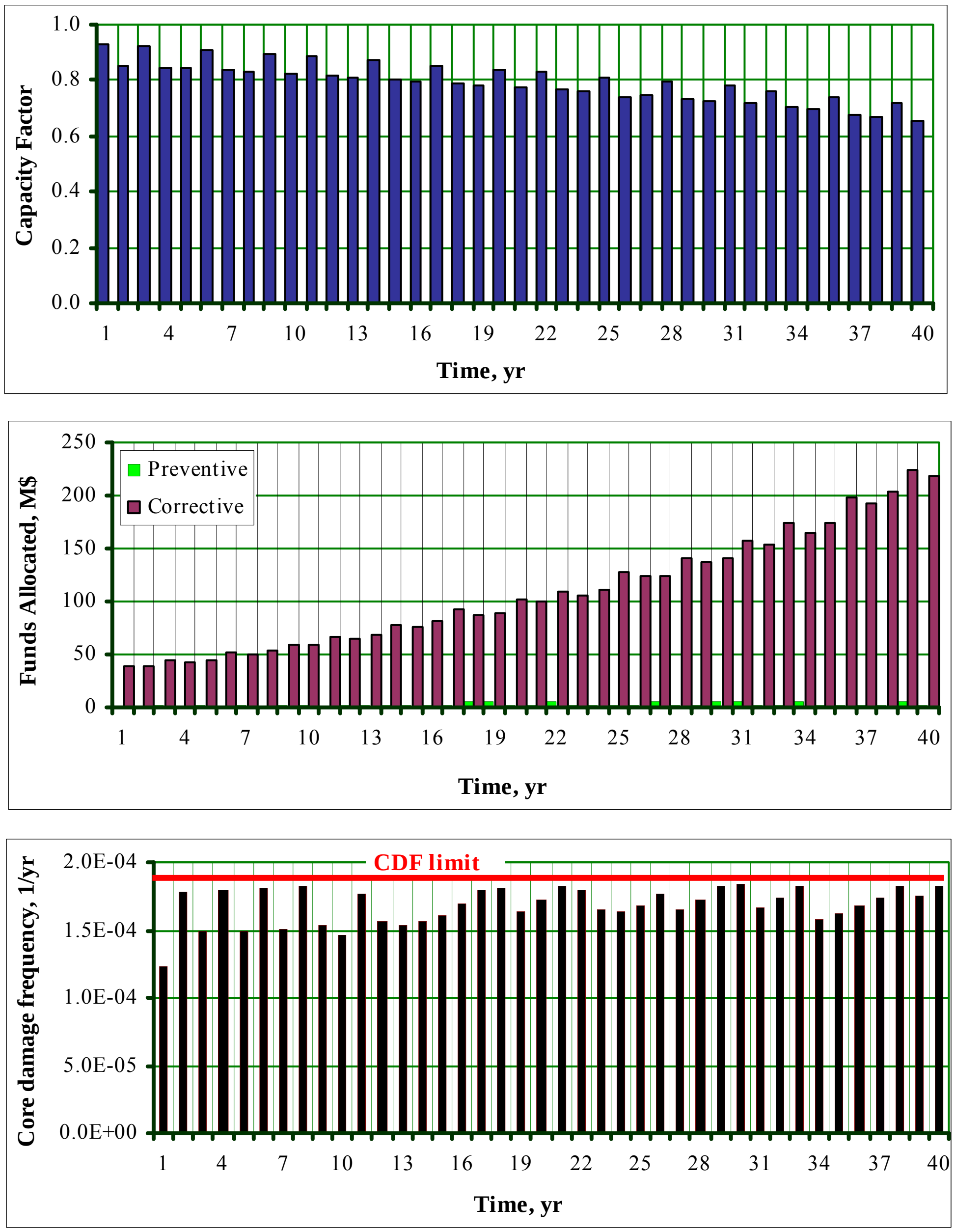
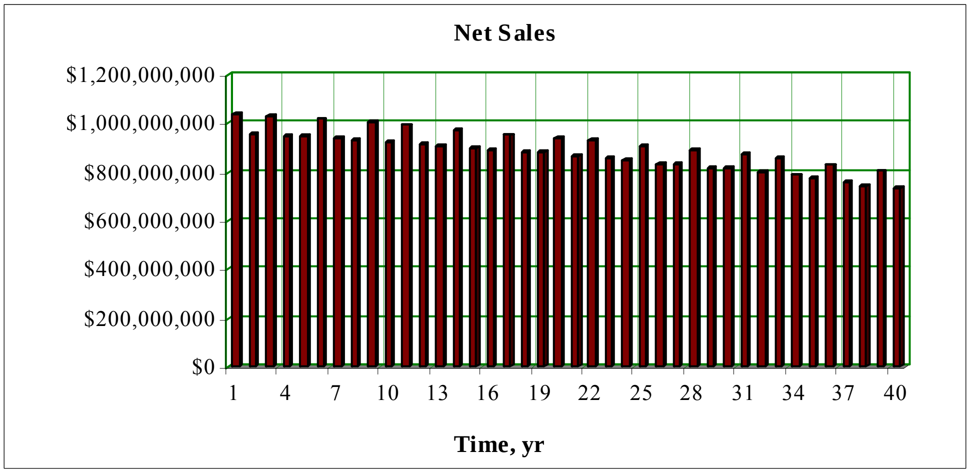


Figure B.13. CDF is kept within 50% of limit



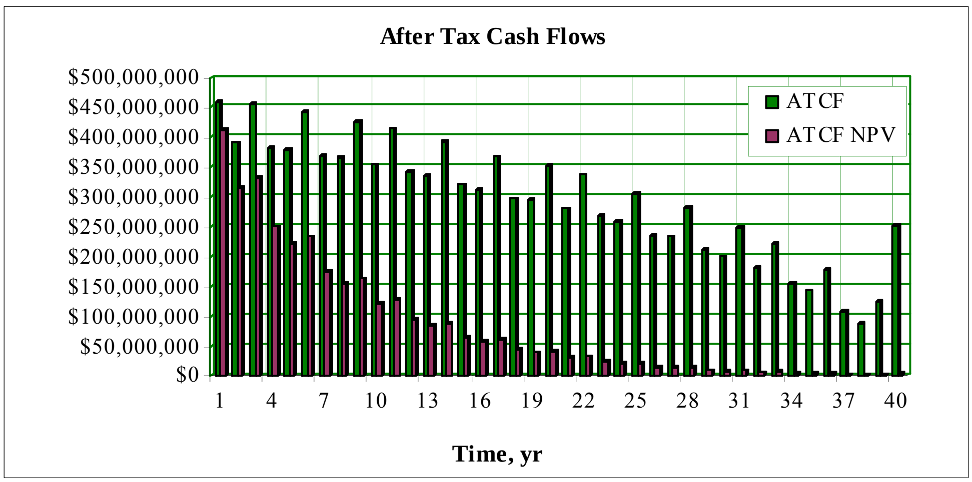


Figure B.14. Financial graphs for the case when CDF is kept within 50% limit

End of Year	Net Sales	Expenses: Production (w/o fuel & maintenance)	Expenses: Fuel	Expenses: Maintenance	Expenses: Outside Services	Expenses: Administrative & General (w/o wages & salaries)	Expenses: Wages & Salaries	Expenses: Total	Depreciation Amount	Loan: Interest	Loan: Principal Reduction	Taxable Income	Taxes	ATCF	ATCF NPV
1	$1,043,912,712	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$27,820,000	$200,000,000	$4,981,968	$669,978,202	$234,492,371	$458,323,863	$412,013,541
2	$959,246,647	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$199,501,803	$5,480,165	$529,960,287	$185,486,100	$390,276,073	$315,391,486
3	$1,032,846,848	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$198,953,787	$6,028,181	$631,287,226	$220,950,529	$455,590,567	$330,972,403
4	$952,260,128	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$198,350,969	$6,630,999	$519,996,390	$181,998,736	$382,648,705	$249,894,287
5	$949,070,323	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$197,687,869	$7,294,099	$514,325,342	$180,013,870	$378,299,424	$222,090,908
6	$1,019,935,124	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$196,958,459	$8,023,509	$613,955,623	$214,884,468	$442,329,697	$233,442,656
7	$940,865,134	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$196,156,108	$8,825,860	$502,735,179	$175,957,313	$369,234,058	$175,176,115
8	$935,835,691	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$195,273,522	$9,708,446	$496,797,021	$173,878,957	$364,491,669	$155,453,235
9	$1,006,155,901	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$194,302,677	$10,679,291	$593,236,394	$207,632,738	$426,206,417	$163,407,190
10	$926,965,869	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$193,234,748	$11,747,220	$483,229,879	$169,130,458	$353,634,253	$121,883,389
11	$994,764,732	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$192,060,026	$12,921,942	$578,273,207	$202,395,622	$414,237,694	$128,344,964
12	$916,092,146	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$190,767,832	$14,214,136	$468,166,302	$163,858,206	$341,376,012	$95,082,641
13	$910,402,240	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$189,346,418	$15,635,550	$460,288,978	$161,101,142	$334,834,337	$83,837,293
14	$976,524,877	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$187,782,863	$17,199,105	$551,641,259	$193,074,441	$392,649,765	$88,379,516
15	$897,797,937	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$186,062,953	$18,919,015	$442,994,742	$155,048,160	$320,309,618	$64,811,978
16	$890,931,595	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$184,171,051	$20,810,917	$433,636,442	$151,772,755	$312,334,822	$56,812,608
17	$954,266,227	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$182,089,959	$22,892,009	$520,853,452	$182,298,708	$366,944,786	$60,001,770
18	$881,921,828	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$179,800,759	$25,181,209	$417,426,855	$146,099,399	$297,428,298	$43,720,452
19	$880,914,610	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$177,282,638	$27,699,330	$417,391,671	$146,087,085	$294,887,307	$38,967,043
20	$943,290,175	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$174,512,705	$30,469,263	$508,352,248	$177,923,287	$351,241,749	$41,724,057
21	$865,726,154	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$171,465,778	$33,516,190	$402,735,015	$140,957,255	$279,543,621	$29,851,695
22	$935,035,559	$79,177,000	$0	$5,000,000	$1,950,000	$18,674,000	$6,500,000	$111,301,000	$51,282,051	$168,114,159	$36,867,809	$495,786,905	$173,525,417	$336,675,731	$32,319,918
23	$858,356,326	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$164,427,378	$40,554,590	$396,040,004	$138,614,002	$268,153,465	$23,140,933
24	$850,226,108	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$160,371,919	$44,610,049	$386,128,183	$135,144,864	$257,655,322	$19,988,288
25	$908,847,834	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$155,910,915	$49,071,053	$466,899,536	$163,414,838	$305,695,696	$21,318,901
26	$832,566,818	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$151,003,809	$53,978,159	$365,008,719	$127,753,052	$234,559,560	$14,705,089
27	$836,978,506	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$145,605,993	$59,375,975	$370,973,424	$129,840,698	$233,038,802	$13,133,539
28	$894,285,200	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$139,668,396	$65,313,572	$455,494,251	$159,422,988	$282,039,743	$14,289,034
29	$818,884,587	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$133,137,039	$71,844,929	$356,628,798	$124,820,079	$211,245,841	$9,620,990
30	$815,173,598	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$125,952,546	$79,029,422	$350,999,042	$122,849,665	$200,402,006	$8,204,888
31	$876,727,800	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$118,049,604	$86,932,364	$438,200,980	$153,370,343	$249,180,324	$9,171,141
32	$802,394,734	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$109,356,367	$95,625,601	$348,145,920	$121,851,072	$181,951,298	$6,020,101
33	$855,837,675	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$99,793,807	$105,188,161	$423,483,364	$148,219,177	$221,358,077	$6,583,897
34	$789,756,945	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$89,274,991	$115,706,977	$338,328,663	$118,415,032	$155,488,705	$4,157,436
35	$779,693,274	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$77,704,293	$127,277,675	$336,175,898	$117,661,564	$142,518,710	$3,425,607
36	$830,699,793	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$64,976,526	$140,005,442	$409,470,631	$143,314,721	$177,432,519	$3,833,875
37	$758,420,792	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$50,975,982	$154,005,987	$322,808,622	$112,983,018	$107,101,669	$2,080,367
38	$747,195,268	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$35,575,383	$169,406,585	$316,756,952	$110,864,933	$87,767,485	$1,532,556
39	$805,293,720	$79,177,000	$0	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$112,301,000	$51,282,051	$18,634,724	$186,347,244	$399,347,409	$139,771,593	$124,510,623	$1,954,466
40	$734,459,350	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$23,540,000	$0	$0	$352,321,318	$123,312,461	$252,548,857	$3,563,742

Accumulated Profit NPV:	**$3,310,303,995**

Figure B.15. Financial statement for the case when CDF is kept within 50% limit

Components	Operating Years																																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Reactor Vessel																																								
Steam Generator #1																																								
Steam Generator #2																																								
Steam Generator #3																																								
Steam Generator #4																																								
Primary Coolant Pump #1																		W												W										
Primary Coolant Pump #2																			W												W									
Primary Coolant Pump #3																						W												W						
Primary Coolant Pump #4																											W												W	
Pressurizer																																								
Turbine																																								
Condencer																																								
Feed Water Pump			W		W		W		W	W		W	W	W	W	W	W	W	W	W	W		W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
Control Rods																																								
Emergency Cooling System																																								

R - replacement, W - work 2

Figure B.16. Work table for the case when CDF is kept within 50% limit

Case 5. Preventive maintenance is just enough to keep system capacity factor above 80% (no safety constraints).

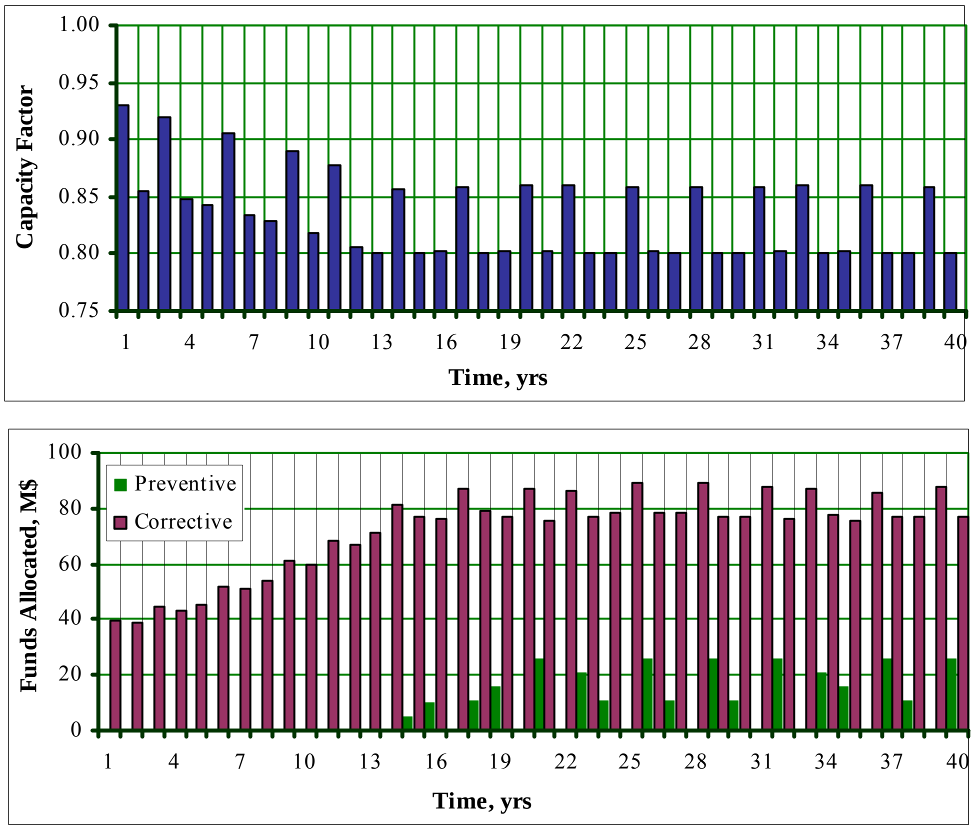
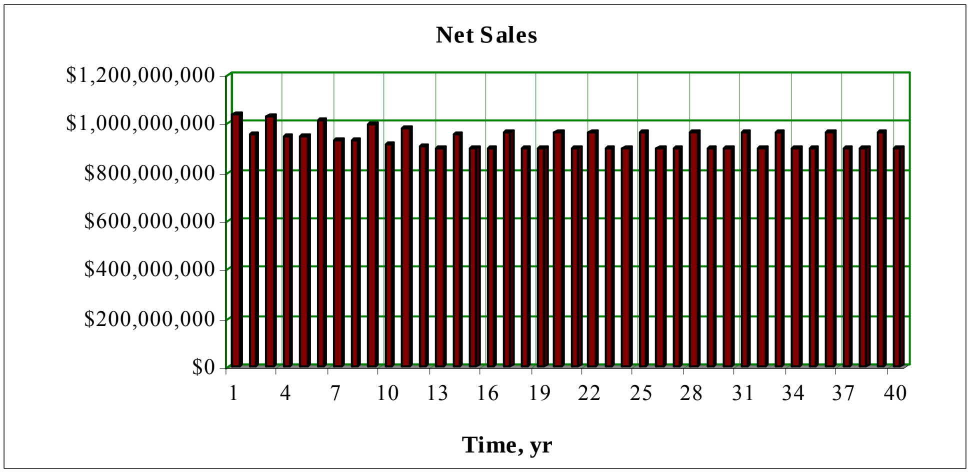


Figure B.17. CF is kept above 80% per year (no safety constraints)

		Expenses								Loan					
End of Year	***Net Sales***	***Production (w/o fuel & maintenance)***	***Fuel***	***Maintenance***	***Outside Services***	***Administrative & General (w/o wages & salaries)***	***Wages & Salaries***	***Total***	***Depreciation Amount***	***Interest***	***Principal Reduction***	***Taxable Income***	***Taxes***	***ATCF***	***ATCF NPV***
1	$1,043,912,712	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$27,820,000	$200,000,000	$4,981,968	$669,978,202	$234,492,371	$458,323,863	$412,013,541
2	$959,246,647	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$199,501,803	$5,480,165	$529,960,287	$185,486,100	$390,276,073	$315,391,486
3	$1,031,489,681	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$198,953,787	$6,028,181	$630,688,429	$220,740,950	$455,201,349	$330,689,648
4	$950,884,763	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$198,350,969	$6,630,999	$518,374,893	$181,431,213	$381,594,732	$249,205,975
5	$946,321,815	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$197,687,869	$7,294,099	$512,082,906	$179,229,017	$376,841,841	$221,235,194
6	$1,016,688,979	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$196,958,459	$8,023,509	$610,122,755	$213,542,964	$439,838,333	$232,127,821
7	$936,346,803	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$196,156,108	$8,825,860	$498,396,220	$174,438,677	$366,413,734	$173,838,066
8	$930,897,535	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$195,273,522	$9,708,446	$490,956,173	$171,834,660	$360,695,117	$153,834,031
9	$999,013,408	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$194,302,677	$10,679,291	$585,780,915	$205,023,320	$421,360,355	$161,549,214
10	$918,974,167	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$193,234,748	$11,747,220	$474,759,573	$166,165,851	$348,128,554	$119,985,798
11	$985,344,647	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$192,060,026	$12,921,942	$567,096,733	$198,483,857	$406,972,986	$126,094,110
12	$905,536,018	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$190,767,832	$14,214,136	$456,627,864	$159,819,752	$333,876,026	$92,993,688
13	$898,188,990	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$189,346,418	$15,635,550	$446,763,831	$156,367,341	$326,042,991	$81,636,077
14	$961,514,904	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$187,782,863	$17,199,105	$534,765,243	$187,167,835	$381,680,354	$85,910,468
15	$898,033,855	$79,177,000	$33,333,333	$5,000,000	$1,950,000	$18,674,000	$6,500,000	$144,634,333	$51,282,051	$186,062,953	$18,919,015	$439,275,322	$153,746,363	$317,891,995	$64,322,792
16	$900,138,036	$79,177,000	$33,333,333	$10,000,000	$1,950,000	$18,674,000	$6,500,000	$149,634,333	$51,282,051	$184,171,051	$20,810,917	$438,650,426	$153,527,649	$315,593,911	$57,405,424
17	$964,524,417	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$182,089,959	$22,892,009	$537,713,030	$188,199,561	$377,903,512	$61,793,709
18	$898,807,028	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$179,800,759	$25,181,209	$438,223,043	$153,378,065	$310,945,820	$45,707,459
19	$900,454,950	$79,177,000	$33,333,333	$16,000,000	$1,950,000	$18,674,000	$6,500,000	$155,634,333	$51,282,051	$177,282,638	$27,699,330	$439,509,559	$153,828,346	$309,263,934	$40,866,802
20	$965,262,812	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$174,512,705	$30,469,263	$545,822,003	$191,037,701	$375,597,090	$44,617,231
21	$900,285,028	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$171,465,778	$33,516,190	$436,316,683	$152,710,839	$301,371,706	$32,182,657
22	$965,051,137	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$168,114,159	$36,867,809	$553,309,591	$193,658,357	$374,065,477	$35,909,228
23	$899,069,868	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$164,427,378	$40,554,590	$445,587,590	$155,955,657	$300,359,395	$25,920,220
24	$898,580,276	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$160,371,919	$44,610,049	$457,908,587	$160,268,005	$304,312,584	$23,607,847
25	$963,357,725	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$155,910,915	$49,071,053	$560,760,835	$196,266,292	$366,705,541	$25,573,665
26	$899,950,728	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$151,003,809	$53,978,159	$453,406,468	$158,692,264	$292,018,097	$18,307,299
27	$899,111,409	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$145,605,993	$59,375,975	$473,044,806	$165,565,682	$299,385,201	$16,872,672
28	$963,748,649	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$139,668,396	$65,313,572	$577,111,309	$201,988,958	$361,090,830	$18,294,014
29	$899,412,058	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$133,137,039	$71,844,929	$472,287,260	$165,300,541	$286,423,841	$13,044,900
30	$898,450,748	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$125,952,546	$79,029,422	$493,615,754	$172,765,514	$293,102,869	$12,000,260
31	$962,928,458	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$118,049,604	$86,932,364	$599,652,880	$209,878,508	$354,124,059	$13,033,620
32	$899,886,904	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$109,356,367	$95,625,601	$497,099,834	$173,984,942	$278,771,342	$9,223,521
33	$964,892,982	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$99,793,807	$105,188,161	$620,555,931	$217,194,576	$349,455,245	$10,393,916
34	$898,404,385	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$89,274,991	$115,706,977	$519,806,234	$181,932,182	$273,449,126	$7,311,445
35	$899,910,860	$79,177,000	$33,333,333	$16,000,000	$1,950,000	$18,674,000	$6,500,000	$155,634,333	$51,282,051	$77,704,293	$127,277,675	$539,989,970	$188,996,489	$274,997,857	$6,609,902
36	$964,690,934	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$64,976,526	$140,005,442	$656,444,226	$229,755,479	$337,965,356	$7,302,590
37	$899,629,188	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$50,975,982	$154,005,987	$554,531,002	$194,085,851	$257,721,216	$5,006,035
38	$898,704,250	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$35,575,383	$169,406,585	$584,117,783	$204,441,224	$261,552,025	$4,567,103
39	$963,244,189	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$18,634,724	$186,347,244	$699,256,226	$244,739,679	$319,451,355	$5,014,487
40	$899,437,616	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$23,540,000	$0	$0	$633,257,776	$221,640,221	$435,157,554	$6,140,551

Accumulated Profit NPV:	**$3,367,534,468**

Figure B.18. Financial statement for the case when CF was kept above 80% per year (no safety constraints)



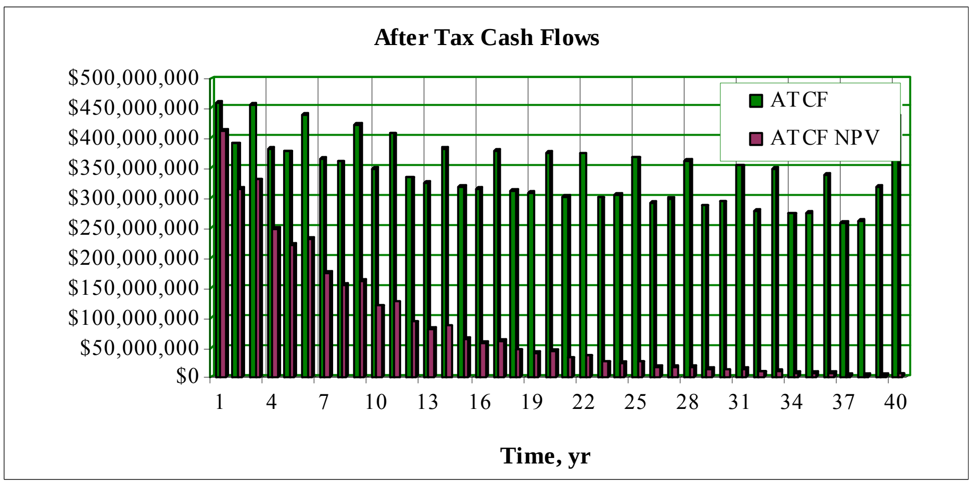


Figure B.19. Financial graphs for the case when CF was kept above 80% per year (no safety constraints)

Components	Operating Years																																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Reactor Vessel																																								
Steam Generator #1																			W		W					W			W	W				W	W			W		
Steam Generator #2																					W		W			W			W	W				W	W			W		
Steam Generator #3																			W		W			W			W		W			W		W			W			W
Steam Generator #4																			W		W					W	W		W			W			W		W			W
Primary Coolant Pump #1																W					W								W								W			
Primary Coolant Pump #2																W							W									W								W
Primary Coolant Pump #3																		W					W									W								W
Primary Coolant Pump #4																		W					W									W								W
Pressurizer																										W											W			
Turbine																																								
Condencer																								W										W						
Feed Water Pump															R			W	W		W		W	W		W	W		W	W		W		W	W		W	W		W
Control Rods																																								
Emergency Cooling System																																								

R - replacement, W - work 2

Figure B.20. Work table for the case when CF was kept above 80% per year (no safety constraints)

Case 6. Preventive maintenance is just enough to keep system capacity factor above 80% (CDF within 100% from the brand new system).

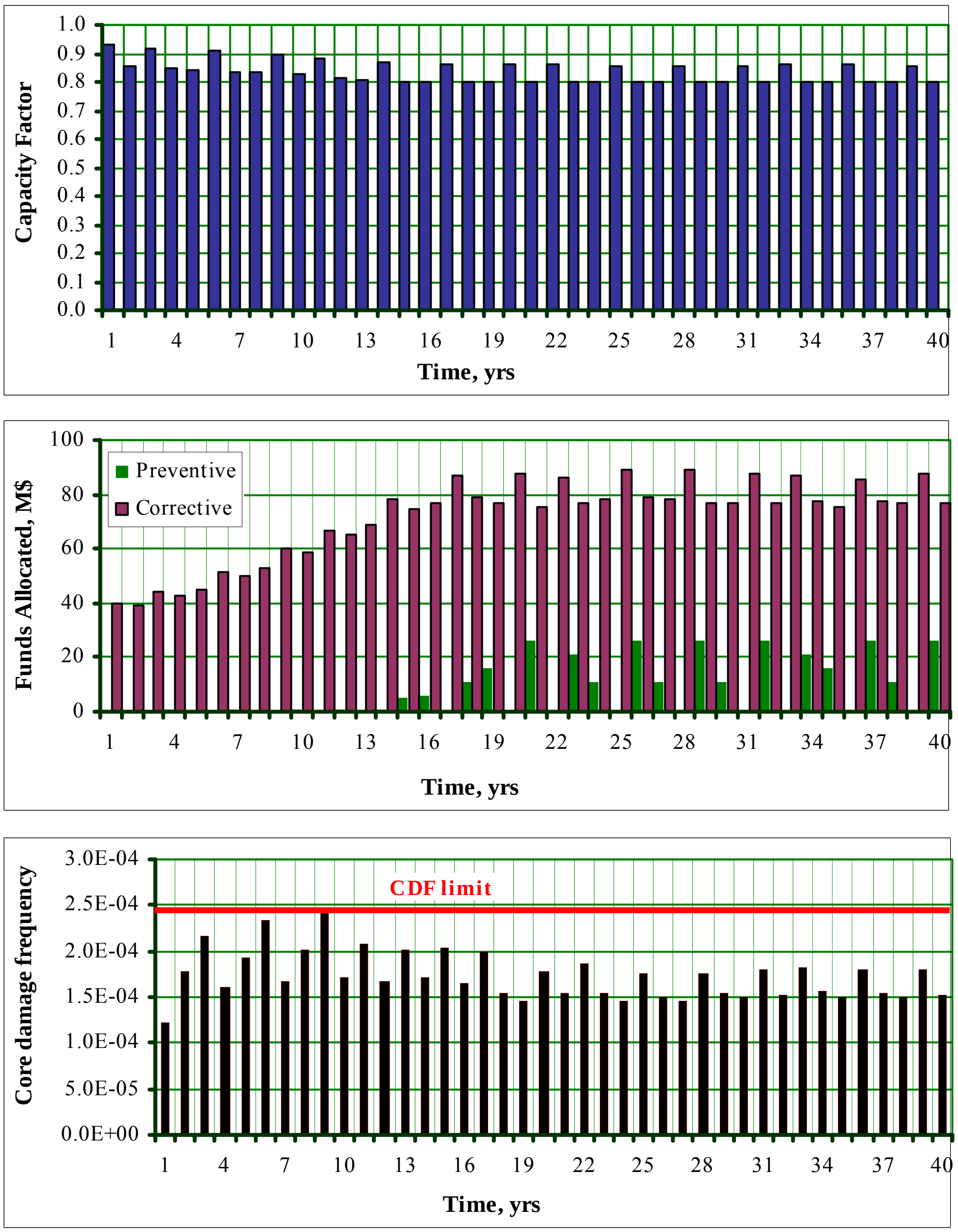
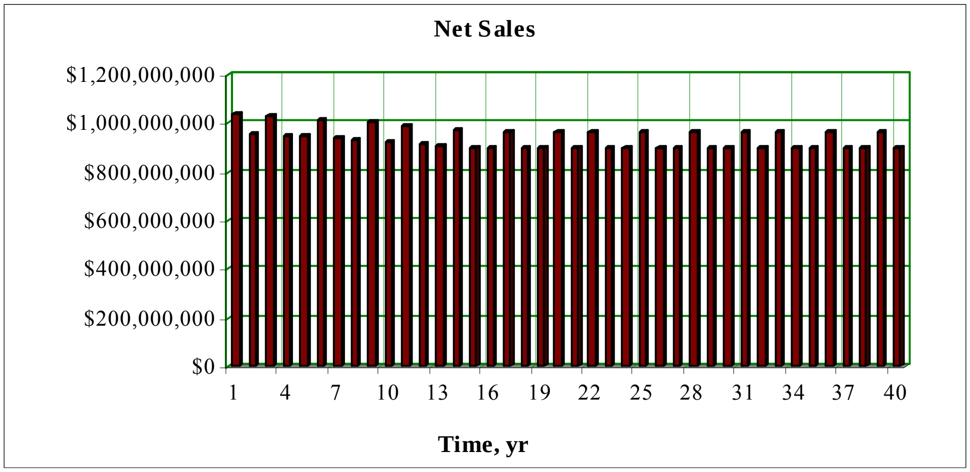


Figure B.21. CF is kept above 80% per year (CDF within 100%)

		Expenses								*Loan*					
End of Year	***Net Sales***	***Production (w/o fuel & maintenance)***	***Fuel***	***Maintenance***	***Outside Services***	***Administrative & General (w/o wages & salaries)***	***Wages & Salaries***	***Total***	***Depreciation Amount***	***Interest***	***Principal Reduction***	***Taxable Income***	***Taxes***	***ATCF***	***ATCF NPV***
1	$1,043,912,712	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$27,820,000	$200,000,000	$4,981,968	$669,978,202	$234,492,371	$458,323,863	$412,013,541
2	$959,246,647	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$199,501,803	$5,480,165	$529,960,287	$185,486,100	$390,276,073	$315,391,486
3	$1,031,489,681	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$198,953,787	$6,028,181	$630,688,429	$220,740,950	$455,201,349	$330,689,648
4	$952,638,568	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$198,350,969	$6,630,999	$519,442,430	$181,804,851	$382,288,631	$249,659,136
5	$948,240,503	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$197,687,869	$7,294,099	$514,346,698	$180,021,344	$378,313,306	$222,099,057
6	$1,018,954,862	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$196,958,459	$8,023,509	$612,798,578	$214,479,502	$441,577,618	$233,045,741
7	$940,566,347	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$196,156,108	$8,825,860	$502,382,369	$175,833,829	$369,004,731	$175,067,316
8	$935,508,997	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$195,273,522	$9,708,446	$496,410,901	$173,743,815	$364,240,691	$155,346,195
9	$1,004,453,270	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$194,302,677	$10,679,291	$592,222,468	$207,277,864	$425,547,364	$163,154,510
10	$926,447,529	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$193,234,748	$11,747,220	$482,616,411	$168,915,744	$353,235,498	$121,745,955
11	$994,153,257	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$192,060,026	$12,921,942	$577,548,732	$202,142,056	$413,766,785	$128,199,061
12	$915,906,154	$79,177,000	$33,333,333	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$140,634,333	$51,282,051	$190,767,832	$14,214,136	$467,945,778	$163,781,022	$341,232,671	$95,042,717
13	$909,496,388	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$189,346,418	$15,635,550	$460,213,785	$161,074,825	$334,785,462	$83,825,055
14	$976,204,004	$79,177,000	$0	$1,000,000	$1,950,000	$18,674,000	$6,500,000	$107,301,000	$51,282,051	$187,782,863	$17,199,105	$551,260,039	$192,941,014	$392,401,972	$88,323,742
15	$901,146,669	$79,177,000	$33,333,333	$5,000,000	$1,950,000	$18,674,000	$6,500,000	$144,634,333	$51,282,051	$186,062,953	$18,919,015	$444,325,610	$155,513,964	$321,174,682	$64,987,017
16	$899,993,808	$79,177,000	$33,333,333	$6,000,000	$1,950,000	$18,674,000	$6,500,000	$145,634,333	$51,282,051	$184,171,051	$20,810,917	$442,436,784	$154,852,874	$318,055,044	$57,853,096
17	$964,354,475	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$182,089,959	$22,892,009	$537,460,634	$188,111,222	$377,739,455	$61,766,883
18	$898,643,134	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$179,800,759	$25,181,209	$437,976,696	$153,291,844	$310,785,694	$45,683,921
19	$900,278,788	$79,177,000	$33,333,333	$16,000,000	$1,950,000	$18,674,000	$6,500,000	$155,634,333	$51,282,051	$177,282,638	$27,699,330	$439,243,204	$153,735,121	$309,090,804	$40,843,924
20	$965,055,544	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$174,512,705	$30,469,263	$545,507,598	$190,927,659	$375,392,727	$44,592,955
21	$900,218,383	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$171,465,778	$33,516,190	$436,228,185	$152,679,865	$301,314,182	$32,176,514
22	$964,971,382	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$168,114,159	$36,867,809	$553,203,878	$193,621,357	$373,996,763	$35,902,631
23	$899,017,415	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$164,427,378	$40,554,590	$445,508,762	$155,928,067	$300,308,157	$25,915,798
24	$898,522,939	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$160,371,919	$44,610,049	$457,822,258	$160,237,790	$304,256,471	$23,603,494
25	$963,290,188	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$155,910,915	$49,071,053	$560,658,861	$196,230,601	$366,639,257	$25,569,042
26	$899,881,369	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$151,003,809	$53,978,159	$453,302,038	$158,655,713	$291,950,217	$18,303,044
27	$899,035,734	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$145,605,993	$59,375,975	$472,930,556	$165,525,694	$299,310,938	$16,868,487
28	$963,659,585	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$139,668,396	$65,313,572	$576,976,423	$201,941,748	$361,003,154	$18,289,572
29	$899,396,019	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$133,137,039	$71,844,929	$472,261,887	$165,291,660	$286,407,348	$13,044,148
30	$898,432,621	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$125,952,546	$79,029,422	$493,587,358	$172,755,575	$293,084,412	$11,999,505
31	$962,907,216	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$118,049,604	$86,932,364	$599,619,440	$209,866,804	$354,102,323	$13,032,820
32	$899,861,944	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$109,356,367	$95,625,601	$497,062,448	$173,971,857	$278,747,042	$9,222,717
33	$964,863,560	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$99,793,807	$105,188,161	$620,511,749	$217,179,112	$349,426,527	$10,393,062
34	$898,374,327	$79,177,000	$33,333,333	$21,000,000	$1,950,000	$18,674,000	$6,500,000	$160,634,333	$51,282,051	$89,274,991	$115,706,977	$519,761,142	$181,916,400	$273,419,816	$7,310,661
35	$899,877,838	$79,177,000	$33,333,333	$16,000,000	$1,950,000	$18,674,000	$6,500,000	$155,634,333	$51,282,051	$77,704,293	$127,277,675	$539,940,410	$188,979,143	$274,965,643	$6,609,127
36	$964,652,038	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$64,976,526	$140,005,442	$656,385,686	$229,734,990	$337,927,305	$7,301,767
37	$899,622,803	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$50,975,982	$154,005,987	$554,520,615	$194,082,215	$257,714,464	$5,005,904
38	$898,696,937	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$35,575,383	$169,406,585	$584,106,067	$204,437,124	$261,544,410	$4,566,970
39	$963,235,647	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$18,634,724	$186,347,244	$699,242,455	$244,734,859	$319,442,403	$5,014,346
40	$899,426,618	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$23,540,000	$0	$0	$633,241,451	$221,634,508	$435,146,943	$6,140,401

Accumulated Profit NPV:	**$3,385,600,967**

Figure B.22. Financial statement for the case when CF was kept above 80% per year (CDF within 100%)



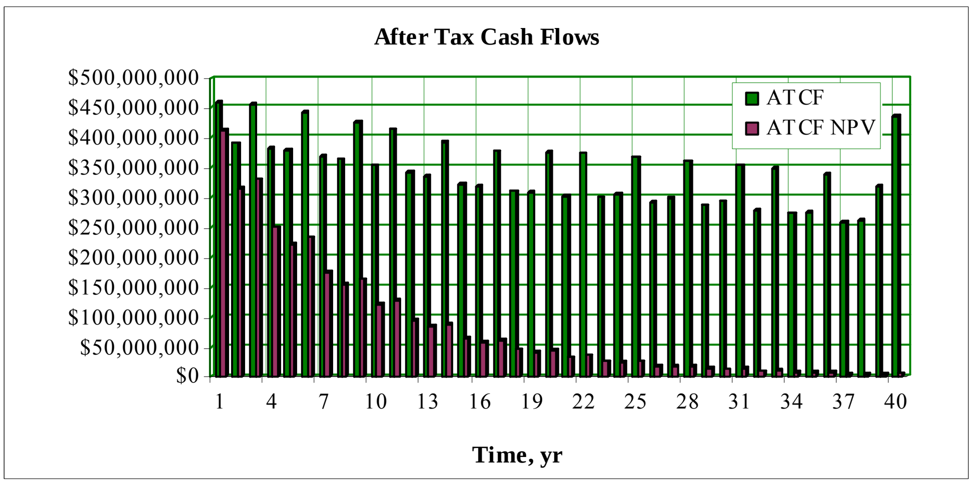


Figure B.23. Financial graphs for the case when CF was kept above 80% per year (CDF within 100%)

Components	Operating Years																																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Reactor Vessel																																								
Steam Generator #1																					W		W			W			W	W				W	W			W		
Steam Generator #2																			W		W					W			W	W				W	W			W		
Steam Generator #3																			W		W			W			W		W			W		W			W			W
Steam Generator #4																			W		W					W	W		W			W			W		W			W
Primary Coolant Pump #1															W						W								W								W			
Primary Coolant Pump #2																W							W									W								W
Primary Coolant Pump #3																		W					W									W								W
Primary Coolant Pump #4																		W					W									W								W
Pressurizer																										W											W			
Turbine																																								
Condencer																								W										W						
Feed Water Pump				W			W			W		W		W		W		W	W		W		W	W		W	W		W	W		W		W	W		W	W		W
Control Rods																																								
Emergency Cooling System																																								

R - replacement, W - work 2

Figure B.24. Work table for the case when CF was kept above 80% per year (CDF within 100%)

Case 7. Preventive maintenance is just enough to keep system capacity factor above 85% (no safety constraints).

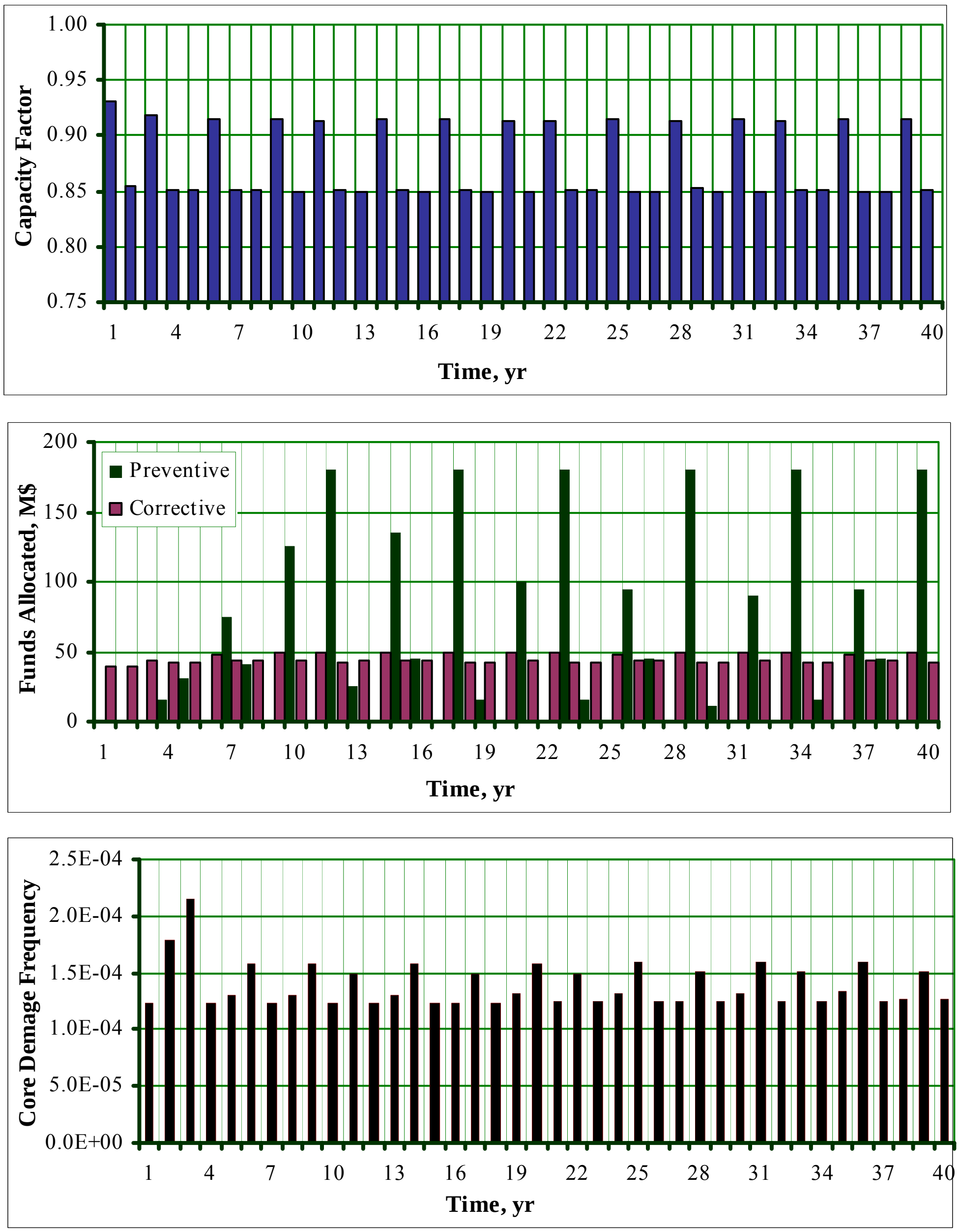
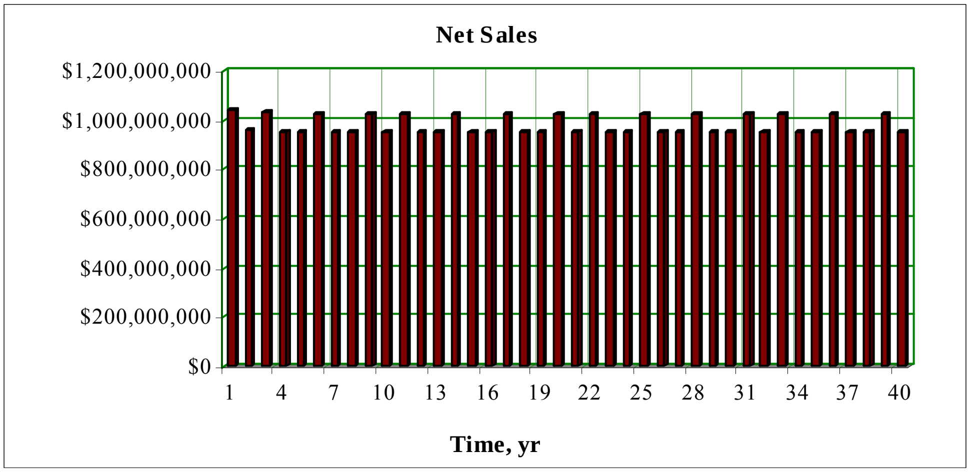


Figure B.25. CF is kept above 85% per year (no safety constraints)

		Expenses								Loan					
End of Year	***Net Sales***	***Production (w/o fuel & maintenance)***	***Fuel***	***Maintenance***	***Outside Services***	***Administrative & General (w/o wages & salaries)***	***Wages & Salaries***	***Total***	***Depreciation Amount***	***Interest***	***Principal Reduction***	***Taxable Income***	***Taxes***	***ATCF***	***ATCF NPV***
1	$1,043,912,712	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$27,820,000	$200,000,000	$4,981,968	$669,978,202	$234,492,371	$458,323,863	$412,013,541
2	$959,246,647	$79,177,000	$33,333,333	$0	$1,950,000	$18,674,000	$6,500,000	$139,634,333	$51,282,051	$199,501,803	$5,480,165	$529,960,287	$185,486,100	$390,276,073	$315,391,486
3	$1,031,489,681	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$198,953,787	$6,028,181	$630,688,429	$220,740,950	$455,201,349	$330,689,648
4	$954,708,798	$79,177,000	$33,333,333	$15,000,000	$1,950,000	$18,674,000	$6,500,000	$154,634,333	$51,282,051	$198,350,969	$6,630,999	$508,274,579	$177,896,103	$375,029,528	$244,918,473
5	$954,615,571	$79,177,000	$33,333,333	$31,000,000	$1,950,000	$18,674,000	$6,500,000	$170,634,333	$51,282,051	$197,687,869	$7,294,099	$492,947,019	$172,531,457	$364,403,514	$213,932,938
6	$1,026,374,723	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$196,958,459	$8,023,509	$623,968,944	$218,389,130	$448,838,356	$236,877,648
7	$954,562,445	$79,177,000	$33,333,333	$75,000,000	$1,950,000	$18,674,000	$6,500,000	$214,634,333	$51,282,051	$196,156,108	$8,825,860	$449,459,094	$157,310,683	$334,604,602	$158,746,825
8	$954,359,486	$79,177,000	$33,333,333	$41,000,000	$1,950,000	$18,674,000	$6,500,000	$180,634,333	$51,282,051	$195,273,522	$9,708,446	$484,116,877	$169,440,907	$356,249,575	$151,938,038
9	$1,026,081,622	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$194,302,677	$10,679,291	$625,213,995	$218,824,898	$446,991,857	$171,376,311
10	$954,221,013	$79,177,000	$33,333,333	$125,000,000	$1,950,000	$18,674,000	$6,500,000	$264,634,333	$51,282,051	$193,234,748	$11,747,220	$401,191,682	$140,417,089	$300,309,425	$103,504,483
11	$1,025,958,961	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$192,060,026	$12,921,942	$626,417,203	$219,246,021	$445,531,291	$138,040,788
12	$955,297,249	$79,177,000	$33,333,333	$180,000,000	$1,950,000	$18,674,000	$6,500,000	$319,634,333	$51,282,051	$190,767,832	$14,214,136	$350,789,134	$122,776,197	$265,080,852	$73,832,334
13	$954,323,717	$79,177,000	$33,333,333	$26,000,000	$1,950,000	$18,674,000	$6,500,000	$165,634,333	$51,282,051	$189,346,418	$15,635,550	$504,983,324	$176,744,163	$363,885,662	$91,111,291
14	$1,026,049,781	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$187,782,863	$17,199,105	$631,678,957	$221,087,635	$444,674,269	$100,089,444
15	$954,346,859	$79,177,000	$33,333,333	$135,000,000	$1,950,000	$18,674,000	$6,500,000	$274,634,333	$51,282,051	$186,062,953	$18,919,015	$398,433,359	$139,451,676	$291,344,719	$58,951,173
16	$954,253,840	$79,177,000	$33,333,333	$45,000,000	$1,950,000	$18,674,000	$6,500,000	$184,634,333	$51,282,051	$184,171,051	$20,810,917	$490,440,525	$171,654,184	$349,257,475	$63,528,709
17	$1,025,992,566	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$182,089,959	$22,892,009	$636,590,410	$222,806,644	$442,173,809	$72,303,006
18	$955,779,400	$79,177,000	$33,333,333	$180,000,000	$1,950,000	$18,674,000	$6,500,000	$319,634,333	$51,282,051	$179,800,759	$25,181,209	$362,687,305	$126,940,557	$261,847,590	$38,490,268
19	$954,264,936	$79,177,000	$33,333,333	$16,000,000	$1,950,000	$18,674,000	$6,500,000	$155,634,333	$51,282,051	$177,282,638	$27,699,330	$527,151,271	$184,502,945	$366,231,047	$48,394,559
20	$1,025,961,838	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$174,512,705	$30,469,263	$645,035,015	$225,762,255	$440,085,548	$52,277,824
21	$954,209,002	$79,177,000	$33,333,333	$100,000,000	$1,950,000	$18,674,000	$6,500,000	$239,634,333	$51,282,051	$171,465,778	$33,516,190	$448,185,268	$156,864,844	$309,086,286	$33,006,475
22	$1,025,949,008	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$168,114,159	$36,867,809	$650,619,161	$227,716,706	$437,316,697	$41,981,166
23	$956,095,012	$79,177,000	$33,333,333	$180,000,000	$1,950,000	$18,674,000	$6,500,000	$319,634,333	$51,282,051	$164,427,378	$40,554,590	$378,738,748	$132,558,562	$256,907,648	$22,170,449
24	$954,498,439	$79,177,000	$33,333,333	$16,000,000	$1,950,000	$18,674,000	$6,500,000	$155,634,333	$51,282,051	$160,371,919	$44,610,049	$544,599,007	$190,609,653	$360,661,357	$27,979,251
25	$1,026,231,803	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$155,910,915	$49,071,053	$664,251,537	$232,488,038	$433,974,497	$30,264,932
26	$954,145,937	$79,177,000	$33,333,333	$95,000,000	$1,950,000	$18,674,000	$6,500,000	$234,634,333	$51,282,051	$151,003,809	$53,978,159	$473,650,307	$165,777,607	$305,176,592	$19,132,236
27	$954,221,297	$79,177,000	$33,333,333	$45,000,000	$1,950,000	$18,674,000	$6,500,000	$184,634,333	$51,282,051	$145,605,993	$59,375,975	$529,303,379	$185,256,183	$335,953,273	$18,933,566
28	$1,025,951,773	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$139,668,396	$65,313,572	$679,342,858	$237,770,000	$427,541,337	$21,660,609
29	$956,504,382	$79,177,000	$33,333,333	$180,000,000	$1,950,000	$18,674,000	$6,500,000	$319,634,333	$51,282,051	$133,137,039	$71,844,929	$410,773,640	$143,770,774	$246,439,988	$11,223,873
30	$954,309,613	$79,177,000	$33,333,333	$11,000,000	$1,950,000	$18,674,000	$6,500,000	$150,634,333	$51,282,051	$125,952,546	$79,029,422	$583,723,249	$204,303,137	$351,672,741	$14,398,236
31	$1,026,012,013	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$118,049,604	$86,932,364	$701,771,916	$245,620,171	$420,501,433	$15,476,655
32	$954,165,730	$79,177,000	$33,333,333	$90,000,000	$1,950,000	$18,674,000	$6,500,000	$229,634,333	$51,282,051	$109,356,367	$95,625,601	$520,341,700	$182,119,595	$293,878,555	$9,723,364
33	$1,025,884,772	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$99,793,807	$105,188,161	$718,971,097	$251,639,884	$413,425,104	$12,296,584
34	$956,128,901	$79,177,000	$33,333,333	$180,000,000	$1,950,000	$18,674,000	$6,500,000	$319,634,333	$51,282,051	$89,274,991	$115,706,977	$453,987,700	$158,895,695	$230,667,079	$6,167,544
35	$954,494,527	$79,177,000	$33,333,333	$16,000,000	$1,950,000	$18,674,000	$6,500,000	$155,634,333	$51,282,051	$77,704,293	$127,277,675	$627,299,261	$219,554,741	$331,748,896	$7,973,981
36	$1,026,223,217	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$64,976,526	$140,005,442	$755,217,537	$264,326,138	$402,168,008	$8,689,849
37	$954,222,988	$79,177,000	$33,333,333	$95,000,000	$1,950,000	$18,674,000	$6,500,000	$234,634,333	$51,282,051	$50,975,982	$154,005,987	$573,815,044	$200,835,266	$270,255,844	$5,249,511
38	$954,287,316	$79,177,000	$33,333,333	$45,000,000	$1,950,000	$18,674,000	$6,500,000	$184,634,333	$51,282,051	$35,575,383	$169,406,585	$639,449,767	$223,807,418	$297,517,815	$5,195,122
39	$1,026,025,758	$79,177,000	$0	$0	$1,950,000	$18,674,000	$6,500,000	$106,301,000	$51,282,051	$18,634,724	$186,347,244	$800,507,548	$280,177,642	$385,264,714	$6,047,571
40	$956,262,802	$79,177,000	$33,333,333	$180,000,000	$1,950,000	$18,674,000	$6,500,000	$319,634,333	$23,540,000	$0	$0	$571,222,009	$199,927,703	$394,834,306	$5,571,545

Accumulated Profit NPV:	**$3,399,551,306**

Figure B.26. Financial statement for the case when CF was kept above 85% per year (no safety constraints)



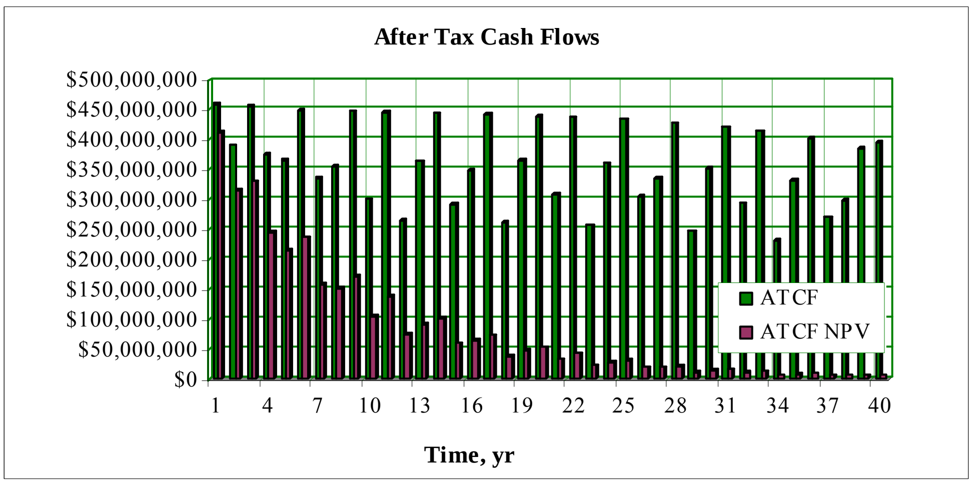


Figure B.27. Financial graphs for the case when CF was kept above 85% per year (no safety constraints)

VITA

Vera Erguina was born in Moscow, Russia in 1976. She received her B.S. degree in physics from Moscow State Engineering and Physics Institute in 1997 from the Department of Theoretical and Experimental Physics of Nuclear Reactors. She received her M.S. degree in 1999 from the same department. Her thesis was in the field of Materials Protection, Control, and Accounting (MPC&A).

She started her Ph.D. program in Texas A&M University at the Department of Nuclear Engineering in 2000 under the direction of Dr. Alan E. Waltar. Later she transferred under the direction of Dr. Paul Nelson, Jr. She graduated with the Ph.D. degree in May 2004.

During her Ph.D. program at Texas A&M, she worked for three summer internships at Argonne National Laboratory in Argonne, IL, and she worked at South Texas Projects Nuclear Operation Company during Fall 2003.

Her permanent address in Russia is: Konstantinova St. 1-11, Moscow, Russia, 129278.